STRONG-MOTION EARTHQUAKE INSTRUMENT ARRAYS

Proceedings
of the
International Workshop on Strong-Motion Earthquake Instrument Arrays

May 2-5, 1978
Honolulu, Hawaii

Convened by

International Association for Earthquake Engineering

Sponsored by

National Science Foundation
United Nations Educational, Scientific and Cultural Organization

Edited by W.D. Iwan

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Foreward

At the meeting of the Executive Committee of the International Association for Earthquake Engineering held on January 14, 1977 in New Delhi on the occasion of the Sixth World Conference on Earthquake Engineering, a decision was made to hold an International Workshop on Strong-Motion Earthquake Instrument Arrays and to seek sponsorship from the United States National Science Foundation and the United Nations Educational, Scientific and Cultural Organization. Subsequently, a Steering Committee was appointed to plan the Workshop.

The Steering Committee held its first meeting at the California Institute of Technology during October 17-18, 1977. It was decided to convene the Workshop in Honolulu during May 2-5, 1978. A list of invitees was drawn up and an outline of topics to be discussed was prepared. The Chairman then undertook to submit a proposal to the National Science Foundation for sponsoring the Workshop, and correspondence was initiated with UNESCO about its participation.

The Workshop was held at Honolulu as planned and the participants worked very hard on the difficult questions of selection of sites for instrument arrays, selection of instrument types, and the design of the arrays which will hopefully provide in the next decade or so data to give better insight into the mechanism of earthquake occurrence and the nature of the forces to which engineering structures are likely to be subjected so that their structural design can be tailored to meet the challenge.

On behalf of the International Association for Earthquake Engineering I thank the participants for their efforts in the interest of science and for the welfare of humanity. The able manner in which Dr. Iwan planned and conducted the Workshop deserves special mention.

It is hoped that the member countries will derive benefit from this report which is submitted herewith for their consideration and further action with respect to the installation of instruments, their maintenance, the processing of data and the exchange of information with all seismic countries of the world. It is also hoped that the respective organizations in member countries will give this program a high priority in the interest of human welfare and thereby minimize disasters resulting from future earthquakes. Cooperation in this venture is invited on a worldwide basis.

Jai Krishna, President
International Association for
Earthquake Engineering

Preface

The International Workshop on Strong-Motion Earthquake Instrument Arrays was held May 2-5, 1978 at the East-West Center, Honolulu, Hawaii. The Workshop was organized by a Steering Committee appointed by the International Association for Earthquake Engineering. This volume is the product of the combined efforts of those in attendance.

The goal of the Workshop was to develop a workable plan for the possible future deployment of dense strong-motion earthquake instrument arrays with primary emphasis on ground motion studies. Three potential areas of array application were considered; source mechanism studies, wave propagation studies and studies of local effects. In order to achieve its stated goal, the Workshop was organized into five working subgroups. The areas covered by the subgroups were: favorable array locations, array design for source mechanism and wave propagation studies, array design for local effects studies, array construction and operation, and implementation. The reports of the individual subgroups are incorporated as chapters in this volume.

Experts in earthquake engineering and seismology were invited from all over the world to participate in the Workshop. Those individuals with specific expertise necessary for the deliberations of a particular subgroup were invited to serve as working members of that subgroup. In addition, a number of individuals were invited as Workshop observers in order to insure a balanced geographical and technical representation.

I would like to express my sincere thanks to all of the participants for their many contributions to the Workshop. I would especially like to thank the subgroup Chairmen; B. A. Bolt, G. W. Housner, R. B. Matthiesen, T-L. Teng and R. V. Whitman who put in many hours both before, during and after the Workshop in order to insure its success. I would also like to express my personal thanks to Miss Sharon Vedrode who so cheerfully and ably handled the many administrative details of the Workshop and the preparation of this volume. Finally, on behalf of all the participants I gratefully acknowledge the United States National Science Foundation and the United Nations Educational, Scientific and Cultural Organization whose financial support made the Workshop possible.

Wilfred D. Iwan
Chairman, Steering Committee

Table of Contents

Resolution

The following resolution was approved unanimously by the delegates of the International Workshop on Strong-Motion Earthquake Instrument Arrays during a general session on May 5, 1978.

The protection of life and property from the devastating effects of earthquakes is an urgent world-wide problem. An understanding of the nature of strong earthquake motions is of crucial importance in solving this problem. At the present time, however, there is a scarcity of engineering data acquired near the centers of destructive earthquakes, and existing instrument arrays are inadequate to provide the necessary data. Yet there is a high probability of occurrence of destructive earthquakes in different parts of the world in the next decade. The participants in this international workshop unanimously recommend that the earthquake-threatened countries and other concerned countries and organizations make a concerted effort to establish a comprehensive world-wide system of specialized strong-motion earthquake instrument arrays capable of resolving the nature of the earthquake source mechanism, wave propagation and local site effects. As a first step, the following specific recommendations should be implemented.

1. The International Association for Earthquake Engineering in collaboration with the International Association of Seismology and Physics of the Earth's Interior form an International Strong Motion Arrays Council to facilitate the establishment of strong-motion earthquake instrument arrays.

2. Earthquake-threatened countries individually and collectively initiate the immediate installation of minimal arrays of 10-20 strong-motion instruments at least at the 28 world-wide sites identified by this workshop.

3. High priority be given to the design and installation of more elaborate source mechanism, wave propagation and local effects arrays, particularly at the six critical sites identified.

4. A mobile strong-motion instrument array capable of making source mechanism, wave propagation and local effects measurements be established and maintained for deployment immediately following the occurrence of a major earthquake for the recording of aftershocks.

Chapter 1

Summary and Conclusions

1.1 INTRODUCTION

Safeguarding life and property from the destructive effects of earthquakes is a major worldwide problem. In spite of the increased awareness of this problem, earthquakes each year claim many lives and cause enormous damage to man-made structures and other facilities. In order to design safe, economical structures and facilities in earthquake prone regions of the world, it is necessary to understand the nature of the ground motion that these systems may be expected to experience during their lifetimes. This understanding can ultimately come only from the measurement and subsequent study of the strong ground motion resulting from actual earthquakes.

The first modern strong-motion accelerographs were designed and installed in 1932 and the Long Beach earthquake which occurred the next year produced the first strong-motion accelerograms. The number of accelerographs grew gradually until the early 1960's. Then, the rate of growth increased markedly until the present level of approximately 5000 instruments deployed worldwide was achieved.

The selection of sites for strong-motion accelerographs has traditionally been made by engineers primarily interested in the earthquake response of buildings and other structures. It is not surprising, therefore, that most strong-motion instruments are concentrated near major population centers. The remaining instruments are spread rather sparsely throughout some of the more accessible seismically active zones of the world. Relatively few strong-motion instruments have been deployed in integrated arrays designed for the purpose of gaining detailed information about the generation, transmission and local modification of strong ground motion.

In the design of major structures and facilities such as important buildings, dams, bridges and power plants, it is highly desirable to know the ground motion at a specific site that would result from a particular earthquake event. As the return period for major earthquakes associated with a given portion of a fault is generally quite long, it is impractical to wait for data from the particular event in question. Instead, it is necessary to extrapolate from data which have been obtained from other events which are thought to be in some sense similar to the particular event under consideration. This extrapolation process can only be reliable if there is an understanding of the individual factors which affect the character of strong ground motion such as; the nature of the source mechanism, the influence of the wave propagation path, and the effect of local topographic and soil conditions.

Generally speaking, isolated single instruments provide insufficient information to give a clear understanding of the factors influencing strong ground motion. What is required are multiple-instrument two- to three-dimensional arrays with configurations tailored to the specific information desired. At the present time, the number of such arrays is inadequate. Only when a greater number of such arrays are operational and data have been gathered will it be possible to significantly improve the accuracy of predictions of the nature of strong ground motion at a particular site.

It is important that future strong-motion arrays be deployed at those locations around the world which provide the greatest potential yield for the sizeable investment required. It is also important that such arrays be designed so as to maximize the usefulness of the data which will be obtained. Both of these objectives can best be met through a program of international cooperation which draws upon the varied resources of different participating countries. It is with this understanding that the delegates of the International Workshop on Strong-Motion Earthquake Instrument Arrays undertook the task of making specific recommendations concerning the location, configuration, and operation of strong-motion arrays. A summary of the recommendations of the Workshop follows.

1.2 FAVORABLE ARRAY LOCATIONS

In compiling a list of promising sites for strong-motion arrays, five principles have been employed: 1) the desirability of attaining a high probability of recording detailed strong-motion information for a damaging earthquake ($M > 6.5$) within the next 10 years, 2) the desirability of recording the near field ground motion for a very large earthquake ($M \geq 8$), 3) the desirability of obtaining data from a variety of different source mechanisms and geotectonic conditions, 4) the desirability of favorable operating conditions and 5) the desirability of the proximity of important industrial and population centers with structures of engineering significance.

Application of these principles and a careful examination of potential sites have led to the selection of 28 locations as being promising for the deployment of strong-motion arrays. These 28 locations are indicated in Figure 1.1. Detailed information about each location is contained in Chapter 2. All important source types are represented including: thrust, strike-slip and vertical slip faults. A variety of geological conditions is represented as well.

Of the 28 locations selected, six have been designated as high priority sites. These sites are judged to have an especially high probability of yielding useful data. The six high priority sites are, in order: Shillong, India; Oaxaca, Mexico; Chia-i, Taiwan; Palmdale, U.S.A.; Suruga-Izu, Japan; and Varto, Turkey.

The favorable locations indicated by the Workshop are not intended to be exhaustive. Countries throughout the world are encouraged to deploy strong-motion earthquake instruments wherever they believe the conditions for such deployment to be favorable. However, the identified locations are believed to be of sufficient importance that the delegates of the Workshop have recommended unanimously that minimal arrays of 10-20 strong-motion instruments be installed immediately at each of these locations. It has further been recommended that high priority be given to the design and installation of more elaborate arrays at the six most promising locations.

1.3 SOURCE MECHANISM AND WAVE PROPAGATION ARRAYS

The ground motion experienced at a given location depends both upon the nature of the earthquake source mechanism and the factors affecting the propagation of waves from the source to the site. In order to gain a fuller understanding of the physical processes involved in this generation and transmission of seismic energy, it will be necessary to obtain data from fairly dense arrays of strong-motion instruments deployed within the near-field region of strong earthquakes. These arrays should have different configurations depending upon the type of source.

Three different source mechanism and wave propagation array configurations have been developed for possible deployment at favorable sites. For sites with a predominantly strike-slip source mechanism, a comb-shaped surface array is recommended consisting of approximately 100 to 200 instruments. About half of the instruments would be deployed along a line on one side of the fault at an average spacing of approximately 10 km. The remaining instruments would be deployed in a number of legs extending from the fault. These legs would extend linearly from 40-100 km with the longer legs being used primarily for the study of path effects. For sites with a predominantly subduction thrust source mechanism, an array consisting of 50-150 instruments is recommended. These instruments would be arranged in two or three parallel lines along the fault with an average spacing of 20 km. For sites with a predominantly dip-slip source mechanism, a two-dimensional array configuration is recommended consisting of approximately 100 instruments with spacings from 2 to 10 km.

In addition to the permanent arrays designed for source mechanism and wave propagation investigations, it is recommended that a mobile array of approximately 50 instruments be maintained for use in measuring the strong ground motion generated by aftershocks following great earthquakes. It is believed that the information gained from magnitude 6-7 earthquakes can be extremely valuable in the study of the generation and transmission of seismic waves as well as in the study of local site effects.

It is recommended that the instruments used in source mechanism and wave propagation arrays be three-component, 2g accelerometers having a bandwidth of 0.1 to 30 Hz and a dynamic range of 10^6. Provision must be made for precise relative timing. Internal clocks should have a very low drift rate and should be externally resettable. All instruments should have pre-event memories and easily adjustable trigger levels.

Details of possible configurations of source mechanism and wave propagation arrays along with recommended instrument characteristics are given in Chapter 3.

1.4 LOCAL EFFECTS ARRAYS

A complete description of earthquake generated ground motion involves more than the characterization of the motion at a particular point. It also requires the description of the gradients of motion which give rise to possible rocking, twisting and relative motion between different points. The precise nature of the motion will be affected not only by the properties of the source and the wave propagation path between the source and site but also by many local factors. These include: localized topographic and soil features, soil-structure interaction effects, soil liquefaction, etc. The nature of strong earthquake ground motion and the way that it is affected by various local conditions can only be adequately understood if additional data are gathered using a system of local effects arrays.

Four general types of local effects arrays are recommended: Local Laboratory Arrays, Simple Extended Arrays, Elemental Arrays and Special Arrays. Local Laboratory Arrays are relatively complex arrays intended to provide data concerning the gradients of ground motion and the nature of wave propagation through a local site. They would consist of from 25 to 40 instruments arranged over an area of up to 1 km^2 and to depths of approximately 100 m. Instruments would measure rotational and relative motion as well as acceleration. Common time bases and simultaneous triggering would be required. These arrays should be deployed in regions where frequent shaking of 0.05g or greater can be expected. They may exist alone or in conjunction with source mechanism and wave propagation arrays.

Simple Extended Arrays are smaller arrays designed to measure systematic variations in ground motion across localized soil, geologic or topographic features. Such arrays would consist of from 6 to 12 accelerometers having common time bases and triggering. Both surface and down-hole instruments would be required.

Elemental Arrays are vertical arrays or horizontal clusters of approximately three instruments contained within a limited area. These arrays would provide data on variations of ground motion with distance and depth. Numerous arrays of this type already exist but their deployment should be expanded.

The Special Arrays recommended are of two types; those intended for soil-structure interaction studies and those intended for liquefaction studies. For soil-structure interaction studies, prototype rigid foundations, simple model building structures and extended buried structures should be instrumented. Rotational accelerometers, strain gauges and pore-pressure transducers would be required in addition to conventional accelerometers. For liquefaction studies, various levels of instrumentation can be employed. However, arrays must have both accelerometers and pore-pressure transducers installed on the surface and to depths of approximately 30 m.

Detailed example configurations for local effects arrays along with a discussion of a possible multi-level deployment strategy are contained in Chapter 4.

1.5 ARRAY CONSTRUCTION AND OPERATION

Several factors affect the cost of construction and operation of a strong-motion array. These include: 1) the availability of field tested instrumentation, 2) local construction and operation capabilities and 3) the availability of standard data processing and dissemination facilities. Information on current strong-motion programs has been used to estimate the costs involved in the major types of arrays recommended herein. In order to enable cost comparisons, a currently available digital accelerograph with a range of 0.001g to 2.0g, a self-trigger and a 2.5 sec pre-event memory has been used as the basic instrument for all arrays. The cost differential involved in changing to other types of instrumentation may be estimated from comparative cost figures given in Chapter 5.

The base cost for installation of a source mechanism and wave propagation array for a strike-slip source is estimated to be approximately $865,000 with an annual operating cost of approximately $84,000. For a subduction-thrust source array, the installation costs would be approximately $655,000 with annual operating costs of approximately $60,000. The corresponding costs for a dip-slip source array would be approximately $830,000 and $80,000 respectively. It is estimated that creation of a mobile array consisting of 50 instruments would cost approximately $475,000 with annual operating costs of approximately $40,000.

A Local Laboratory Array capable of centrally recording 90 channels of acceleration data from surface and down-hole sensors is estimated to have a base installation cost of approximately $519,000 and an annual operating cost of $24,000. These figures would increase if instruments such as pore-pressure sensors were added. No detailed cost estimates for Simple Extended, Elemental or Special Arrays are given due to the large number of variables in their design. However, the cost figures presented for other types of arrays can readily be used to establish costs for specific array configurations of these types.

The above cost figures are based on arrays located in California, U.S.A. A site cost adjustment factor for each of the 28 promising sites considered has been determined based on the probable type of array to be deployed and the degree of difficulty in conducting operations at the different locations. The site factors range from 1.0 to 3.0. It is recommended that each array or local combination of arrays have its own operating headquarters staffed wherever possible by local personnel but if necessary supplemented by trained personnel from other areas.

With respect to data processing and dissemination, it is recommended that three regional data centers be established to handle the worldwide assembling, processing and dissemination of data. These three centers would be in North America, Asia, and either Europe or the Middle East. A standard data format should be agreed upon by all centers. The centers should store all earthquake and station information in a telephone accessed computer and bulletins should be circulated every three months describing records obtained. Floppy disks and cassettes should be used for the exchange of individual earthquake records.

1.6 IMPLEMENTATION

The implementation plan recommended is intended to be flexible and is therefore not rigidly defined. It is believed that array programs should be controlled by the participating scientists and this would appear to preclude any highly developed international inter-governmental structure at the present time. It is, however, felt that it is possible and indeed beneficial to tie the implementation plan for strong-motion arrays to the International Association for Earthquake Engineering (IAEE). This organization with members from all over the world is dedicated to the goals of the strong-motion program and could provide the necessary focal point for international cooperation.

It is recommended that the IAEE in consultation with other organizations such as the International Association of Seismology and Physics of the Earth's Interior (IASPEI) appoint an International Strong Motion Array Council (ISMAC). This Council would be responsible for the initial organization of the implementation structure and would, among other things, prepare general guidelines for array deployment, recommend priorities for array locations and coordinate the world wide assembling and dissemination of data.

In order to assist it in its responsibilities, ISMAC would appoint five Committees. These ISMAC Committees would have responsibility in the following areas: 1) Data Projects, including the preparation of catalogs of existing and future data; 2) Intensive Instrumentation Arrays, including source mechanism and wave propagation arrays; 3) Regional Arrays, including stand alone Local Laboratory Arrays and Simple Extended Arrays; 4) Local Arrays, including Elemental Arrays and Special Arrays; and 5) Mobile Arrays.

It is recommended that a Steering Committee be formed for the planning and execution of each individual array project. This Steering Committee would formulate overall design and operation plans for the array. Such Steering Committees would be encouraged to work closely with the relevant ISMAC Committee thereby optimizing their effort from an international point of view. Where no Steering Committee is established or where such a structure is deemed inappropriate, it is strongly recommended that some other mechanism be found for liaison and information transfer between those responsible for the individual array project and the relevant ISMAC Committee.

At the present time, individual countries are proceeding with unilateral array projects as they see fit and some effort has been directed toward the creation of bilateral projects. However, there appears to be no existing workable structure for the execution of multi-lateral projects. It is hoped that the implementation structure recommended herein will help to make such multilateral cooperation possible in the future.

1.7 CONCLUSIONS

Based upon the findings of the International Workshop on Strong-Motion Earthquake Instrument Arrays it is concluded that:

1) Ample promising sites exist for the deployment of dense strong-motion earthquake instrument arrays. These sites are distributed throughout the seismically active regions of the world and represent a variety of different source mechanisms and tectonic conditions. There are a number of sites for which there appears to be a very high probability of obtaining useful strong-motion data within ten years.

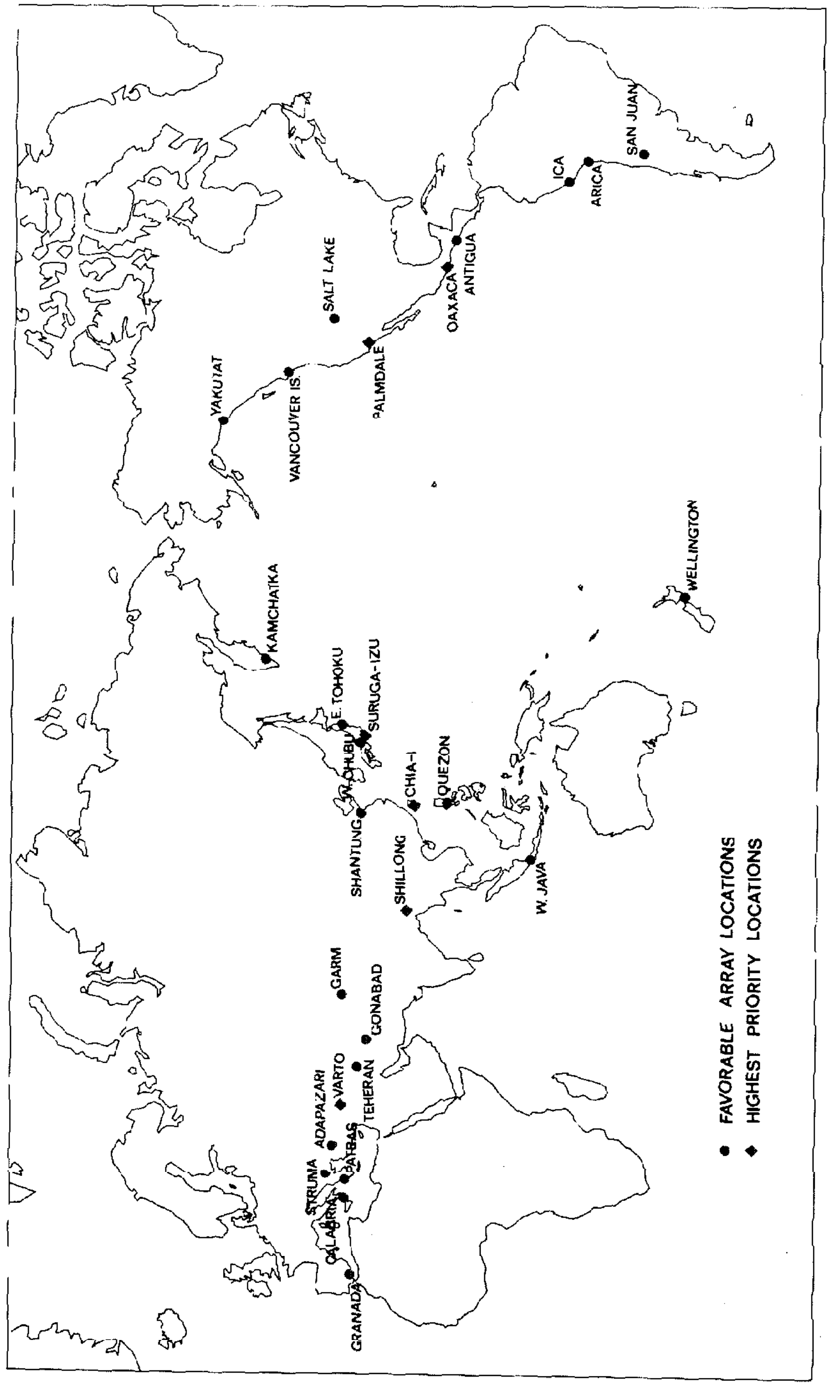
2) There is an adequate understanding of the nature of earthquake ground motion to be able to design useful strong-motion arrays which will provide answers to some of the important unresolved questions facing the designers of structures and other facilities in the earthquake prone regions of the world. Furthermore, instrumentation presently available or under development is adequate for use in these arrays.

3) The cost of deploying strong-motion arrays, although great, is not excessive considering the magnitude of the benefit to be derived from such deployment.

4) Most of the countries affected recognize that the earthquake problem is worldwide in scope and can best be solved by the collective efforts of all concerned. It appears, therefore, that international cooperation is possible and that a workable structure for this cooperation can be established.

In light of the above conclusions, it remains only to get on with the task of designing and deploying strong-motion earthquake instrument arrays.

FIGURE 1.1. FAVORABLE WORLD WIDE LOCATIONS FOR STRONG-MOTION ARRAYS



Chapter 2

Favorable Array Locations

2.1 INTRODUCTION

Seismology became a global and quantitative discipline only when sensitive seismographs were designed just before the turn of the century. By the first decade of the century a network of seismographs of various types was in existence around the world. This network provided the basic material for the spectacular improvement of our knowledge of the Earth's interior.

After World War II, a very much improved international system of earthquake observatories for the recording of distant events was set up by the U.S. Coast and Geodetic Survey, entitled the World-Wide Standardized Seismographic Network (WWSSN). Commencing in 1961, the U.S. Coast and Geodetic Survey was charged with entering into agreements with various national observatories for installing the equipment. The necessary funds from the United States were made available because of the importance this network had for the efforts to obtain a comprehensive nuclear test ban treaty. The seismographs used were the best available at the time. They consisted of six components - one set of three short-period seismographs and one set of three long-period seismographs.

By 1967 the network was essentially complete; total costs (at that time) reached $10,000,000 under Project Vela Uniform. Foreign countries in which the instruments were placed also made large contributions in observatory facilities and manpower and in other ways as well. WWSSN stations were all operated by national organizations in the various countries. Instrumentation was turned over to the local observatories and all records were kept in the country to be used for whatever purpose was deemed proper. The only obligations were that the local observatory send originals of the records to the United States Coast and Geodetic Survey to be copied and returned, and that technicians from the Survey be allowed to service the instruments during the period of mutual agreement. As it turned out, WWSSN seismograms were invaluable in research, not only on nuclear test detection, but on all aspects of seismology. The records were available without restriction to any seismologist in any country, although some countries chose not to participate. Today, the records from this system have been used by seismologists in practically every nation in which research in seismology takes place.

The WWSSN model is not entirely appropriate, of course, for a worldwide system of strong-motion arrays. The purpose behind it is different in important ways, and the world situation is not the same as in the early 1960's. In particular, the measurements of ground motions in strong earthquakes are urgently needed for use in designing earthquake-resistant structures. Nevertheless, it is felt that certain aspects of the great international effort made earlier in seismology in connection with the recording of distant earthquakes can be helpful in the conception of a new world network of strong-motion seismographs in the late 1970's.

2.2 PROBLEMS REQUIRING STRONG-MOTION MEASUREMENTS

Because damaging earthquakes are widely distributed in time and space, the choice of favorable sites for strong-motion arrays must be guided by the principal needs of the users of the records obtained. Progress in our understanding of strong ground motion and response of engineering structures clearly depends upon more measurements of seismic waves near to the source of the earthquake and in regions where their intensity is a maximum. It is relatively easy to set forth a list of the main problems which need to be addressed. On the one hand, there are important questions to do with the pattern of dislocation along a rupturing fault, the influence of soft surficial layers over the source, the scattering of wave energy, the focusing of waves due to underground structures, the variation in wave amplitude, phase and frequency due to attenuation, and the effects of variations in crustal and surficial structure and ground topography. In order to model mathematically the near field response, observational data must be obtained in various geological environments from earthquakes of various sizes and fault mechanisms.

On the other hand, there is a need to be able to predict sufficient details of the pattern of wave motion in a given area or for a particular site so that design accelerograms can be developed. This will involve the prediction of the spectral content of the ground motion from those sources which are likely to shake a particular structure during its lifetime. Because of heightened demand, numerous methods of predicting strong ground motion and response parameters have come into vogue in recent years. These methods and theories are not yet founded on any wide variety of data. In planning a standardized network it is important to keep in mind the need to test many of the present theories. Questions such as the effect of soils on traveling seismic waves, soil-structure interaction and the effect of out-of-phase components of surface waves over the base of large structures also require an enhanced data base.

2.3 SPATIO-TEMPORAL PREDICTION OF SITES

Establishment of a siting plan for strong-motion arrays requires a survey of all seismically active zones of the world in order to select those which provide practical sites which are likely to be shaken by significant earthquakes within a reasonable time. It is necessary, therefore, to consider the likelihood of earthquakes in the various areas and thereby make predictions of the probability of the various levels of seismic intensity over defined areas.

There are at least two possible strategies in the selection of sites for strong-motion arrays.

1) One strategy is to record (for the first time) strong shaking of the ground near the largest magnitude earthquake sources. Such earthquakes are sparse and their sources are accessible in only a limited number of places around the world. The odds, therefore, of trapping such events are slim, but the rewards would be very great, both for seismology and for earthquake engineering. Much of modern strong ground motion seismology and earthquake risk assessment for large structures in urban areas is now weakly based on large extrapolations from moderate earthquake records. There are possibilities that the estimates of hazards are being in some ways grossly overestimated and in others grossly underestimated, with concomitant great economic consequences.

2) Another strategy is to site standardized strong-motion arrays in regions where there are many sources of moderate earthquakes. In areas where earthquakes are frequent, the return for the capital in scientific investment can be guaranteed in a short time. Of course, not only are strong-motion measurements from moderate earthquakes directly useful for engineering purposes, but they are of great importance in seismological studies of methods of scaling between energy levels.

2.4 PRINCIPLES OF SITE SELECTION

The most up-to-date earthquake catalogs, geological maps, and seismic risk studies have been used to make a region-by-region survey of promising sites for strong-motion arrays. The overall aim has been to produce a short list of promising sites in many seismically active regions around the world, rather than concentrating attention on two or three regions or countries. Five specific principles for site selection have been employed. Clearly, in some active regions, such as California, several more-or-less equally satisfactory sites could be chosen following these principles. However, it is assumed that in each country final site selection decisions would probably be made based upon local input and expertise. The five principles employed in site selection are:

1) The need to attain a high probability of capturing a potentially damaging earthquake ($M > 6.5$) within the next ten years. In this regard, consideration has been given to return periods, existence of seismic gaps, current seismicity and occurrence of large historical earthquakes.

2) The need to record for some sites the near field ground motion for very large shocks ($M \sim 8$).

3) The need to obtain data from a variety of source mechanisms (strike-slip, thrust, normal and reverse vertical faults) and of geotectonic conditions such as subduction zones, intraplate, and tensional areas.

4) The need for good operational conditions (accessibility to the area, availability of power, technological assistance, existence of strong motion instruments, etc.).

5) Where feasible, the proximity to important industrial and population centers with structures of engineering significance.

2.5 SUGGESTED PROMISING LOCATIONS

Application of the principles listed above has produced 28 promising locations for strong-motion arrays. These are listed in Table 2.1. The table also contains much of the data upon which the decisions for selection were based. More detailed information on most sites is summarized in the next section.

Some effort has been devoted toward assigning priorities to the 28 sites selected. However, since the favorable locations presented in the table are not at all exhaustive but are meant only to give a minimum list of suggestive array locations, it seems best not to provide any detailed priority rating of all sites at this time. It is recognized that many countries not on the list nonetheless may have strong reasons for establishing and operating special strong-motion arrays and they should certainly be encouraged to do so.

Although no prioritizing of all sites has been presented, it has been determined that six locations from the 28 representative sites given in Table 2.1 are extremely promising for the successful deployment of strong-motion instruments and arrays in the next few years. These highest priority sites, in order, are:

India, Shillong
Mexico, Oaxaca
Taiwan, Taisan, Chia-i
California, Palmdale
Japan, Suruga-Izu
Turkey, Varto

It is of interest to give rough assessments of the probability of successful recording based on the estimates of trigger probabilities given in Table 2.1. For the 28 sites, if each trigger probability is taken equal and reduced to 10 per cent for a five-year span, then the odds of at least one recording are almost unity, or essentially certain success for a joint array program.

For the six highest priority sites, a probability of 0.8 for a ten-year span gives 95 per cent odds of success. Even if the probability at each array is reduced to 10 per cent, the odds of successfully recording

TABLE 2.1. SOME SUGGESTED PROMISING LOCATIONS OF STRONG MOTION ARRAYS

(The list is by no means exhaustive but is suggestive only.)
(For nomenclature, see notes at end of Table.)

Source Type	Country	Area (Fault)	Source: Thrust	Source: Strike Slip	Source: Normal/Reverse	Source: Subduction Zone	Source: Intraplate	Focal Depth	Nearby Maximum Feasible Earthquake Magnitude	Nearby Maximum Historical Earthquake Magnitude and Intensity	Trigger Probability Per 10 Yrs. Acc > 0.2g M > 6.5	Local Seismicity	Geological Conditions: Topp.	Geological Conditions: Rock Type	Geological Conditions: Mapped	Geological Conditions: Geotec.	Operating Conditions: Power	Operating Conditions: Access	Operating Conditions: Existing SM Inst.	Operating Conditions: Maintain	Operating Conditions: Local Op	Possible Operating Agency
S/R	Argentina	San Juan (San Juan)		x	R		x	C	7.5	7. 1944 X	.2	ML	HV	AM	Yes	C	Yes	E	Yes	Yes	Yes	
S	Bulgaria/ Yugoslavia	Struma			x		x	C	7.75	7.75 1904 X	.2	M	H	SMA	Yes	S	Yes	E	Yes	Yes	Yes	GI/ IEEES
TS	Canada	Vancouver Is. (Queen Charlotte)		x				C	8+	7.3 1946	.3	M	H	MA	Yes	S	Yes	M	Yes	Yes	Yes	Ottawa
T	Chile	Arica	x			x		CL	8+	8.5 1868	.5	MH	HM	SA	Yes	S	No	EM	No	Yes	Yes	UCC
S	China	Shantung		x			x	C	8+	8.5 1668	.1	LG	P	λ	Yes	S	Yes	E	Yes	Yes	Yes	Harbin
T	Guatemala	Antigua	x			x		CL	8.5	8.3 1902	.7	H	HM	CMVA	No	C	No	D	No	No	No	?
S	Greece	Patras (Nearby)		x		x		CL	7.5	7. 1953 X	.5	MH	H	SA	Yes	C	Yes	M	Yes	Yes	Yes	SIA
TS	India	Shillong (Dauki-Haflong)	x	x	R			CL	8.7	8.7 1897 XII	.8	MG	HM	SAM	Yes	C	Yes	EM	Yes	Yes	Yes	SRTEE
T	Indonesia	Western Java (Sumatra?)	x	x		x		CL	8	8.1 1903	.2	H	H	VSM	Yes	S	Yes	E	No	Yes	Yes	Met. Ag.
S	Iran	Gonabad (Dasht-e-Bayaz)		x			x	C	7.5	7.3 1968 X	.2	H	H	ASV	Yes	C	No	EM	Yes	Yes	Yes	Ferdowsi Univ.
TS	Iran	Teheran (North-Teheran)	x	x			x	C	8	7.2 1962 X	.2	MG	HM	ASV	Yes	S	Yes	E	Yes	Yes	Yes	PBO
N/R	Italy	SW Calabria			N			CL	7.5	7.3 1905 X	.2	M	PH	AMC	Yes	C	Yes	E	Yes	Yes	Yes	CNEN
TS	Japan	Eastern Tohoku (Nearby)	x			x		CL	8	7.9 1968	.3	H	HM	SV	Yes	S	Yes	EM	Yes	Yes	Yes	(STA, MOC, MOT, Uni, JMA)
TS	Japan	Suruga Bay-Izu (Nearby)	x	x		x		CL	8	8.4 1854	.4	HMG	HP	AVS	Yes	C	Yes	E	Yes	Yes	Yes	
S	Japan	Western Chubu (Neodani)		x			x	C	8	7.9 1891	.2	M	HM	CSV	Yes	C	Yes	E	Yes	Yes	Yes	
T	Mexico	Oaxaca	x			x		CL	8.5	8.5 1903	.9	H	H	CMAV	No	S	No	M	No	Yes	No	UNAM
N/R	New Zealand	Wellington (Wellington)		x			x	C	8+	8.5 1848	.1	M	HM	NA	Yes	S	Yes	E	Yes	Yes	Yes	DSIR
T	Peru	Ica	x			x		CL	8+	8.1 1942 IX	.4	G	HM	SA	Yes	S	No	E	No	Yes	Yes	IGP

Source Type	Country	Area (Fault)	Source: Thrust	Source: Strike Slip	Source: Normal/Reverse	Source: Subduction Zone	Source: Intraplate	Focal Depth	Nearby Maximum Feasible Earthquake Magnitude	Nearby Maximum Historical Earthquake Magnitude and Intensity	Trigger Probability Per 10 Yrs. Acc > 0.2g M > 6.5	Local Seismicity	Geological Conditions: Topp.	Geological Conditions: Rock Type	Geological Conditions: Mapped	Geological Conditions: Geotec.	Operating Conditions: Power	Operating Conditions: Access	Operating Conditions: Existing SM Inst.	Operating Conditions: Maintain	Operating Conditions: Local Op	Possible Operating Agency
S	Philippines	Quezon (Luzon)	x	x				C	8.5	8.1 1897	.6	M	H	VSAM	Yes	C	No	M	No	Yes	Yes	PAGASA
N/R	Spain	Granada (Nearby)			x			CL	7.0	7. 1884 X	0.1	M	HM	SMC	Yes	C	Yes	E	Yes	Yes	Yes	IGN
S	Taiwan	Chia-i (Meitzekeng)		x			x	C	7.5	7.1 1941 IX	.9	H	P	AS	Yes	S	Yes	E	Yes	Yes	Yes	IES
S	Turkey	Adapazari (N. Anatolian)		x			x	C	8+	7.1 1967 IX	.4	M	P	MSA	Yes	S	Yes	E	Yes	Yes	Yes	MRR-METU
S	Turkey	Varto (N. Anatolian)		x			x	C	8	8.0 1939	.6	H	HM	CSM	Yes	C	Yes	M	Yes	Yes	Yes	MRR-METU
S	USA	Palmdale, CA (San Andreas)		x				C	8.5	8¼ 1857 X	.3	MG	H	CSMA	Yes	S	Yes	E	Yes	Yes	Yes	CDMG
N/R	USA	Salt Lake, Utah (Wasatch)			N		x	C	8	7.2 1932 VIII	.1	LG	HPM	CSMA	Yes	S	Yes	E	Yes	Yes	Yes	USGS
T	USA	Yakutat, Alaska (Fairweather)	x	x		x		CL	8.5	8.5 1899	.6	HG	HM	CMA	Yes	C	No	M	Yes	Yes	No	USGS
S	USSR	Garm (Nearby)	x	x			x	C	7.5	7.25 1949	.2	M	M	SARM	Yes	C	Yes?	M	Yes	Yes	Yes	IFZ
T	USSR	S. Kamchatka	x			x		CL	8.5	8.4 1952	.4	H	H	?	Yes	C	Yes	M	Yes	Yes	Yes	IFZ
	Peru[3]	Cordillera		x	R		x	C	7.5	7.+ 1960	(.8)	M	M	SMA	Yes	S	No	MD	No	-	-	IGP-Ceresis

LEGEND

Source Type:

T = thrust
S = strike-slip
N/R = vertical motion (normal/reverse)

Focal Depth:

C = crustal, < 30 km
L = lithosphere, < 100 km

Local Seismicity:

H = high
M = moderate
L = low
G = gap

Topography:

P = plain
H = hill
M = mountain

Rock Type:

C = crystalline
S = sedimentary
A = alluvial
M = metamorphic
V = volcanic

Geotectonics:

S = simple
C = complex

Accessibility:

E = easy
M = moderate
D = difficult

NOTES

1. The statistics of source types are, of the 28 earthquakes listed:

Thrust	T	13
Strike-slip	S	18
Vertical-slip	N/R	5

2. A further subdivision is:

Subduction zone	10
Intraplate	12

3. This site is one suggested as particularly promising for location of a mobile strong-motion array capable of rapid field deployment to a region of aftershocks.

a great earthquake are 1 in 2. Such favorable odds are, of course, a consequence of combining the individual probabilities at each site for the advantage of all.

2.6 DETAILED SITE DESCRIPTIONS

Argentina, San Juan. In this region, earthquakes cause both strike-slip and reverse faulting. The most recent damaging earthquakes occurred in 1944 and 1977 with magnitudes of 7.8 and 7.5. Faults have substantial vertical as well as horizontal motion. Intensities are high and the area is easily accessible. Some strong-motion records have been obtained.

Bulgaria/Yugoslavia, Struma. This area is noted for the occurrence of the strongest shallow earthquake in continental Europe during the 20th century on 4 April 1904 ($M = 7.75$, X-XI MCS). During the period from 1901-1970 there were two earthquakes with magnitude 6.2-6.6, two earthquakes with magnitude 6.7-7.1 and one earthquake of intensity IX and three of intensity VIII were observed. Within 100 km of the area there are other active areas (Central Bulgaria, N. Greece) where several earthquakes of magnitude 7 have originated. The area is presently monitored by three accelerographs in Bulgaria and five accelerographs in Yugoslavia representing a joint cooperative effort by the IEEES in Skopje and the Geophysical Institute in Sofia.

Canada, Vancouver Island. The section of Canada which seems most suitable for the location of a large strong-motion array is along the Pacific margin. The area forms part of the highly seismic boundary running from southeast Alaska along the ocean margin adjacent to Vancouver Island to the west. The largest and most active fault system in the area is the Fairweather - Queen Charlotte Island fault. It acts as the transform plate boundary between the North American and Pacific plates. The fault is similar in many respects to the San Andreas fault in California and has the same right-lateral strike-slip sense of movement. The length of the onshore segment of the Fairweather fault is 280 km in Alaska. The offshore segment, in continuation with the Queen Charlotte Island fault off Canada, is another 470 km.

The seismicity maps for Canada show Queen Charlotte Island and Vancouver Island as having the highest probability of strong ground motion in Canada. Maximum credible earthquake magnitudes for the Queen Charlotte Island fault are usually assessed at 8 or greater. Studies of the occurrence relations for the region indicate that expected maximum rock accelerations exceeding 0.25g to 0.3g occur on the average every 100 years.

Queen Charlotte Island has experienced strong shaking from earthquakes in this century. In this area the fault zone runs close to the islands giving the opportunity for the recording of large strike-slip earthquakes by strong-motion instruments within the very near field. The last major earthquake occurred in August 1949 with latitude 53.75°N and longitude 133.25°W.

To the south, the earthquake locus swings to the west of Victoria Island, associated with the Queen Charlotte transform, and most earthquakes are at a distance of over 100 km from the island. Nevertheless, historically, potentially damaging earthquakes have been located both on and around Vancouver Island. There is a west-east zone between the main concentration (near 130°W, 50°N) and the center of Vancouver Island (near 126°W, 50°N). The largest historical earthquake on the island occurred on June 23, 1946 (M = 7.3) and caused damage in central Vancouver Island. This island would be more accessible and technical services should be readily available for the installation of an extended strong-motion array than the Queen Charlotte Islands, although the latter may be closer to major earthquakes.

Chile, Arica. The Arica region has suffered a number of great earthquakes, most recently in 1868 (M = 8.5). There is a gap for large earthquakes, but the seismicity for moderate events (M ⩾ 6) is fairly high. The fault mechanisms are of the thrust type. The return period for large earthquakes seems to be about 65 years, but this is quite variable. The area is easily accessible.

China, Shantung. Three possible sites for strong-motion arrays have been suggested within The People's Republic of China. It is well-known that the Tanshang-Peking and Shansi regions have been severely damaged by historical destructive earthquakes. The former region was struck once again by a large earthquake in 1976 (M = 7.5). The latter region seems difficult to access due to geographical and topographical reasons.

A third possible site would be the Shantung region. This region was shaken by destructive earthquakes in 1668 (M = 8.5) and in 1837 (M = 7.0). There have also been ten major earthquakes with magnitudes greater than 6.5 over the past 430 years. Tectonically, this region is characterized by several strike-slip faults trending mainly in NE-SW directions. The geological structure is Paleozoic rocks and Tertiary sediments. Reasonable accessibility and power supplies could be expected.

Guatemala, Antigua. The whole region of Central America is subject to continuous earthquake activity. Priority has been given to Guatemala due to the recent destructive earthquake of February 4, 1976. This earthquake took place on the Motagua fault. The general region has been the site of very large earthquakes, such as those of 1902 (M = 8.3) and 1942 (M = 8.3). Several large earthquakes have also occurred within the century in the offshore region and in the nearby south coast of Mexico. Seven earthquakes of M > 6.5 have occurred in the last 100 years with epicenters not separated by more than 200 km.

The proposed site is the region around Antigua or Mazatenango, directed toward the seismicity of the coast more than to that associated with the Motagua fault. Tectonically, the region of the coast corresponds to a subduction zone with the Motagua fault crossing normally to the subduction line. Due to its vicinity, strong-motion instruments would also be triggered by shocks in Nicaragua and San Salvador. Accessibility to the area may be a problem.

Greece, Patras. The site belongs to the most active earthquake belt of Europe. It is located at the crossing of the Hellenic arc with the seismoactive fault extending from the east and covers the region of Patras and the Ionian islands. The Hellenic arc is the boundary between the African and Eurasian plates, the African plate dipping towards the center of the Aegean Sea at a small angle of approximately 20-30°. Considering the area defined by 36°-40°N, 20-22°E, the number of earthquakes of magnitude greater than 6.2 is 16 for the period 1901-1970. The "b" value is 0.90 for $M > 4.8$. There were 24 earthquakes of intensity IX to XI during the period 1801-1900. The strongest shock of the 20th century occurred on 12 August 1950 ($M = 7.0$). Shallow shocks in this area are always accompanied by many aftershocks. Intermediate depth shocks are rare. Most shocks belong to a transcurrent fault type with most fault motions roughly along the NW-SE striking fault planes. The area is easily accessible.

India, Shillong. The Shillong Plateau which was the scene of one of the greatest earthquakes in 1897 with a magnitude 8.7 shows close to the highest seismic activity in the world. The region is bounded by seismically active regional thrust faults and the Dhubri tear fault forms the Western boundary. The Dauki fault forming the southern boundary of the plateau is the most active fault zone of the region. This fault zone merges with the Haflong-Disang thrust zone forming the eastern boundary of the plateau. Towards the north, the plateau is separated from the Assam basin by east-west trending basement faults.

Earthquakes are felt almost daily in various parts of the Shillong Plateau and surrounding areas. Twenty five hundred minor and micro earthquakes were recorded from 1970-1973 within a distance of 440 km from the WWSSN Seismological Observatory at Shillong. Twenty earthquakes with magnitude greater than 5.8 and ten earthquakes with magnitude greater than 6.5 have occurred along the southern and eastern boundary of the Shillong Plateau, east of Dauki and north and northeast of Haflong during the last 70 years. The intervening Dauki-Haflong fault zone has shown medium local seismicity during this period forming a seismic gap along the Dauki-Haflong fault zone. The frequency-magnitude distribution gives an "a" value of 3.8 (40 year period value) and "b" value of 0.45. The low "b" value indicates existence of high shear stress in the region. The observed precursor times for earthquake occurrence in the past in the mezoseismal area of the great Assam earthquake of 1897 are noted to be 23, 28, 8 and 6 years for earthquakes of magnitude 7.8 (1869), 8 (1896), 6.7 (1950) and 5 (1975). The trigger probability per ten years with ground acceleration greater than 0.2g ($M > 6.5$) is thus very high and is estimated at 0.8.

Indonesia, Western Java. Destructive earthquakes occur at frequent intervals off the coast and in the Indonesian islands which lie north of the Sunda trench extending through the lesser and greater Sunda Islands to the Indian Nicolsar and Andaman Islands. More than 20 earthquakes of magnitude greater than 5 and two earthquakes of magnitude greater than 6 have occurred during the last 70 years in Western Java, fifteen of which were responsible for damage to structures. In three events tsunamis occurred along the coast. The frequency-magnitude distribution of data from 1965 to 1975 gives Log N = 7.30-0.94 M. The Semangko fault, following the Bukit Barisan Mountain belt in Sumatra, extends towards the southeast and traverses through the Banten region in which earthquakes are likely to occur in the future. Destructive earthquakes have occurred east, southeast and northwest of this region and the probability of occurrence of an earthquake with magnitude greater than 6.5 is thought to be 0.1-0.2. The Western Java region consists of sedimentary, alluvial and volcanic rocks.

Iran, Gonabad. The Nimboluk Valley to the south of Gonabad, in Northeastern Iran, has been one of the most active seismic regions of that country during the past ten years. The 80 km long fault trace associated with the 1968 Dasht-e-Bayaz earthquake is now a prominent tectonic feature running E-W and intersecting another fault system at almot right angles to the east. Following the 1968 main shock, four $M > 6.0$ earthquakes have thus far occurred in this region. Recent earthquakes indicate that the regional strain energy is not completely released and the possiblity exists that other strong earthquakes may occur within the next ten years. Subsequent to the workshop on September 16, 1978 an earthquake with M = 7.7 occurred in this area.

Iran, Teheran. This area has been seismically active in historical time. Rey, a once large and prosperous city to the south of Teheran, was destroyed several times during the last 2000 years. In this century several major earthquakes have caused destruction and loss of life in the neighboring regions to the east, north and west of Teheran. The seismicity map for the last 20 years shows a very distinct seismic gap in the immediate vicinity of Teheran. It is believed that these indications point to a high likelihood of the possibility of occurrence of a major earthquake ($M \geq 7$) within the next 30-50 years. There are several large dams and high-rise buildings in and around the city of Teheran.

Italy, Southwest Calabria. The largest earthquakes in the 20th century occurred on September 8, 1905 (M = 7.3, I = XI MCS) and 28 December 1908 (M = 7 (Messina), r_{VIII} = 50 km). During the 19th century five shocks of intensity IX-X and seven shocks of intensity VIII± were observed in the area defined by 37-39°N, 15-17°E.

The area is tectonically complex; shallow shocks mark the boundary of a plane dipping steeply below the Tyrrhenian Sea (hypocenters down to 450 km). The active volcanoes Etna and Stromboli are located close to the area. In the Calabrian arc most shocks display normal faults with a dip-slip fault motion.

Ten accelerographs operate now in the area within the Italian network run by CNEN, Rome, where good technical facilities exist for proper operation and data processing.

Japan, Eastern Tohoku. This region has been frequently hit by large shallow earthquakes off the coast of Sanriku and southeast off Hokkaido, as well as by moderate inland earthquakes. The latest large offshore earthquake in this region (M = 7.5) occurred on June 12, 1978. There have been 150 major earthquakes with magnitudes greater than 6.5

since 1900 including the Tokachi-oki earthquake of 1968 (M = 7.9) which caused extensive damage. Most of these earthquakes appear to have thrust-type faulting due to the subduction of the Pacific plate, except for a few large normal fault earthquakes in 1933 and 1938. This region is covered by Paleozoic and intrusive rocks. It has easy accessibility. The extent of the region could be 150 km x 50 km.

Japan, Suruga Bay-Izu. This region includes a rather wide area extending from southern Kwanto-Izo peninsula to the southern Tokai regions. Southern Kwanto was the site of the following destructive earthquakes: 1703 Genvoku (M = 8.2), 1855 Edo (M = 6.9) and 1923 Kwanto (M = 7.9). These earthquakes seem to have been caused mainly by thrust faulting with combined strike-slip along the Sagami trough over a fault dimension of 180 km x 100 km. Geology in this region is mainly of Tertiary and Quaternary sediment.

The Izu peninsula is bounded by the Sagami and Naukai troughs, and regarded as the site of collision of the Philippine plate against the Asiatic continental plate. Many conjugate sets of strike-slip geological faults exist there, and three major earthquakes have occurred in and around the peninsula: 1830 North Izu (M = 7.0), 1874 South Izu (M = 6.9) and 1878 Ziu-Oshima (M = 7.0). The geology of this area is mainly of Quaternary rocks. Since 1800 there have been 28 major earthquakes with magnitudes greater than 6.5 in the above regions.

In the southern Tokai region there has been a reoccurrence of extremely large earthquakes with magnitudes exceeding 8.0 at an interval of about 110 years. The latest one was the 1854 Ansei earthquake. The Suruga Bay region is now regarded as a large seismic gap. The mechanism of earthquakes in this area is of pure thrust type faulting over a dimension of 120 km x 80 km. Geology in this area is mainly Mesazoic. Rupture depths are shallower than 40 km. Accessibility to these regions is excellent, and strong support from government and local authorities may be expected. The extent of the whole region could be 150 km x 80 km.

Japan, Western Chubu. In this region, there are many conjugate sets of active geological faults with right-lateral and left-lateral strike-slip movements which are believed to have been caused by compressional stress working in an E-W direction. Major faults here are Neodani, Atera, Atotsugawa, etc. The largest inland earthquake (M = 7.9) in Japan hit this region in 1891, and 12 major earthquakes with magnitudes greater than 6.5 also took place in and around the region. The tectonic structure is rather complicated. The geology is mainly of Paleozoic rocks sometimes covered by volcanics. The region could have an extent of 150 km x 150 km and is easily accessible.

Mexico, Oaxaca. Situated on the Guerrero-Oaxaca complex massif of the southern end of Sierra Madre the site is in a very active seismic region. Tectonically it belongs to a subduction zone with predominant thrust faulting. The latest damaging earthquake took place in 1968 (M = 6.5). In the last 100 years there have been 14 earthquakes of magnitude greater than 6.5. Four of these earthquakes having magnitudes ranging from 7.5 to 7.9 took place in 1928. The largest shocks in this area, M > 8.5, took place in 1903 and 1899. This is felt to be one of the most likely sites to be subjected to a destructive shock within the next ten years. Mexico has a network of 57 accelerographs extending from north to south, but few in the Oaxaca region.

New Zealand, Wellington. The tectonics of New Zealand are complicated with the occurrence of both shallow and intermediate depth earthquakes. Some damaging earthquakes have occurred which have not been associated with fresh surface fault rupture.

Perhaps the most suitable site for a large strong-motion array is one to the northeast of Wellington on the North Island near the fault trace of the great 1855 earthquake. This trace can still be followed on the ground and passes about 25 km from Wellington. It strikes northeastward. In the 1855 earthquake, the country to the west was uplifted with indications of upthrow of 1 to 3 m. The fault trace is over 100 km long. This earthquake was widely felt and did serious damage in Wellington. There have been no further major earthquakes on this fault in the last 122 years and the site must be considered a good prospect.

Historically, there have been other large shallow focus earthquakes with magnitudes greater than 7 in the vicinity. For example, the Awatere earthquake of October 19, 1948 was felt very strongly on both sides of Cook Strait, and led to three deaths in Wellington. The source was apparently the Awatere fault situated in the northeast corner of the South Island. The most recent sizeable earthquake near the suggested site was on June 24, 1941, and was probably produced by fault-slip roughly parallel to that of 1855 but about 15 km to the east. This earthquake also was strong enough to cause damage in Wellington and more severe damage in the town of Masterton.

Additional advantages of the site north of Wellington are the immediate availability of technical staff associated with the New Zealand Seismological Observatory headquartered in Wellington and the ready access by road to the area.

Peru, Ica. Major earthquakes occur offshore due to the underthrusting of the East Pacific plate. These earthquakes can be very large, with magnitudes greater than 8.0. They do extensive damage to coastal and near coastal (> 50 km) cities. Intensities of IX to X have been reported. The mechanisms are predominantly of thrust type.

Ica is in an apparent seismic gap. To the south there was a magnitude 8.1 earthquake in 1942 from which intensities greater than VIII were observed over about 180 km along the coast and extending 80 km inland. The size of the gap (150-200 km) and the long time without a major earthquake make it likely that a similar large and destructive earthquake will occur in Ica. The area is easily accessible by a major highway.

Philippines, Quezon. The Philippine Archipelago is bounded off the east coast about a hundred or so kilometers by active subduction faults known as the Philippine Trough and the Mindanao Trench. Another fault known as the Philippine Master fault crosses central Luzon southeastwardly from the Lingayen Gulf to Dingalan Bay in Quezon Province. This fault skirts southward close to the east coast of Quezon Province, southward along the west coast of Becal Peninsula, down to eastern Visayas, and then to Mindanao where it splits and forms the graben between the provinces of Surigao and Berkidnun.

Seismicity of the Philippines shows that earthquakes of about magnitude 4 and above are felt about 13 times in northern Luzon annually, 9 times in central Luzon and Manila, 16 times in the Mindanao area, and to a lesser extent in other parts of the country. Since World War II, the major earthquakes that have occurred are: Isabela, Luzon, 1949 (M = 7); Bical Peninsula, 1954 (M = 7); Lake Lanao, Mindanao, 1955 (M = 7.6); Casiguran, eastern Luzon, 1968 (M = 7.3); eastern Quezon, Feb. 1970 (M = 7.2); southwestern Mindanao, Aug. 1976 (M = 7.5). The return period is approximately 20 years.

Spain, Granada. This site belongs tectonically to the zone of interaction of the African plate with the Iberian peninsula. Geologically it is in the complex zone of the de Betica Range. Seismically, it is active at a moderate level with a return period for magnitude 6 earthquakes of about 15 years. Historically, the latest destructive earthquake took place in 1884 with magnitude 7.0 producing widespread damage and loss of life (800 dead). Since the site is near the epicentral zone of the deep earthquake of 1954, it would also provide data of considerable seismological interest if such an earthquake were repeated. The area is now highly developed with large urban structures mainly along the coast. At present, there are three strong-motion instruments located at Granada, Malaga and Almeria.

Taiwan, Chia-i. The Chia-i area is one of the most active seismic areas in Taiwan. Two earthquakes with magnitude 7.1 have occurred in the area since 1900. Statistics show that the area has a recurrence rate of one magnitude 7.0 earthquake per 30 to 40 years. Considering that the last magnitude 7.1 earthquake was in 1941, it seems highly probable that another earthquake of similar magnitude may occur in the area within the next ten years. Earthquakes in the area are all shallower than 35 km. Many of the major earthquakes in the past were acompanied by surface faulting of strike-slip dislocation.

The area is heavily populated and easily accessible. Major engineering structures such as dams and bridges are located in the area. Secondary ground effects due to past earthquakes are commonly observed.

The Institute of Earth Sciences in recent years has installed three telemetered seismographic stations and six SMA-1 accelerographs in this area. The staff of the Institute would be available to provide necessary local support for a strong-motion array.

Turkey, Adapazari and Varto. Since the beginning of the century, 151 earthquakes of intensity greater than VII or magnitude larger than or equal to 6.0 have been recorded in Turkey.

Investigations show that every six years, on the average, five earthquakes of intensities VIII or more (M > 6.5) take place somewhere in Turkey. The number of earthquakes of different magnitudes occurring between the years 1900-1970 is: 56 earthquakes with M = 6.00-6.49, 41 earthquakes with M = 6.50-6.99, 16 earthquakes with M = 7.00-7.49 and 6 earthquakes with M = 7.50-8.00.

One of the main fault lines is the North Anatolian fault which is about 2000 km long extending from the Easian Sea border of Turkey to the Iranian border. The Northern Anatolian fault started active movements after a strong earthquake occurring in 1939. The North Anatolian fault is a strike-slip fracture with slip towards the left. A recent study of Turkey shows a released total energy level of 10^{20} ergs/km^2 associated mostly with the North Anatolian fault zone.

USA, Palmdale, California. The Southern California region is intersected by numerous active faults capable of releasing a magnitude 6.5 or greater earthquake. On the basis of historical seismicity, approximately 60 earthquakes of magnitude 6 or greater are expected every 100 years in this region. The San Andreas fault is the most prominent active fault in the region having the capability of generating magnitude 8+ shallow focus earthquakes. The segment of the San Andreas fault judged most likely to release a large earthquake within the next few years is the Palmdale segment, located approximately 50 km northeast of Los Angeles. A magnitude 8+ earthquake is likely to experience a fault rupture length of 350 to 400 km having a strike-slip source mechanism at a shallow focal depth. A properly located strong-motion instrument array will provide the opportunity to record near-field strong motion at a number of different geologic conditions including: crystalline rock, sedimentary rock, and varying depths of alluvial deposits.

This array will also have a high probability of recording more than one earthquake of different sizes from multiple sources because of the large number of active faults in this region associated with the San Andreas fault. The predominant source mechanisms would be strike-slip and dip-slip thrust.

The proximity to metropolitan Los Angeles would allow the recorded strong ground motion to be calibrated with building damage. There is an existing network of several hundred strong-motion accelerographs in the Los Angeles region and ample technical talent available to maintain a complex array.

USA, Salt Lake, Utah. The Wasatch fault is a major crustal discontinuity that represents the most important structural element of the Intermountain seismic zone. This zone has experienced several damaging earthquakes in the magnitude range of 6 to 7.5 within the short 130 years of historic record. The Wasatch fault is capable of generating a magnitude 8, shallow focus earthquake. The segment of the Wasatch fault judged most likely to release a damaging earthquake within the next few years is the segment located within 10 km of several major populated areas. A magnitude 7.5 or greater earthquake is likely to experience a fault rupture length of at least 100 km having a dip-slip normal source mechanism at a shallow focal depth. A properly located strong-motion instrument array would provide the opportunity to record strong motion at a number of different geologic conditions including: crystalline rock, sedimentary rock, metamorphic rock, and varying depths of valley alluvium.

All of the sites are easily accessible. There are several existing strong-motion accelerographs along the Wasatch fault and ample technical talent available to service and maintain a complex array. Because of the geometry of the fault the source of an earthquake along the Wasatch fault could lie directly beneath a major populated area.

USA, Yakutat, Alaska. The Yakutat Bay region of Alaska is classified as a seismic gap in that it is overdue for large magnitude earthquakes. In 1899 there were at least four magnitude 8+ earthquakes in the region. The Fairweather fault is the major fault in this region that is associated with a subduction zone. The source mechanism is expected to be both strike-slip and thrust having shallow focal depth.

A properly located array would provide the opportunity to record near-field strong ground motion at both metamorphic rock and alluvial sites. Access to the area would be mostly by boat. There are presently no existing important engineering structures nearby; however, in the near future there will be offshore oilfield drilling platforms as well as a major LNG port facility.

USSR, Garm. This seismic zone, approximately 100 km long and 50 km wide including the well-known Garm region, has experienced at least three earthquakes exceeding magnitude 7 since 1930. The last major earthquake occurred in 1949 and had a magnitude 7.25-7.50. The northern half of this region contains the granitic (high Q) Tien Shan mountain range, while the southern half contains the metamorphosed and folded sedimentary (low Q) Pamir mountain range.

There are a wide variety of source mechanisms and local site conditions. There are now 10-20 SMA-1 (analog) stations installed in this region under a joint USGS-USSR program and seven digital SMA-type recorders. The highly active Hindu-Kush deep seismic region is within a few hundred kilometers of this area.

USSR, South Kamchatka. The region belongs to the active belt of the NW Pacific and is marked by a high seismic activity with earthquakes in the crust and in the upper mantle. There were about 40 earthquakes of $M > 5$ during 1965-1974. The recent largest events of the 20th century close to the coast were the earthquakes of 4 November 1952 ($M = 8.4$) and 4 May 1959 ($M = 8.0$). The damage caused in the eastern part of Kamchatka reached intensity X (MM). The region has been thorougly investigated and detailed microzoning studies exist. It is assumed that some strong-motion instruments are presently installed in this area.

Suggested Mobile Array Site

Peru, Cordillera. Shallow intraplate earthquakes caused by horizontal compression occur over most of Cordilleran Peru. In the south, Arequipa was badly damaged in 1960 (having been destroyed many times in its history). Further north, Cusco was severely damaged in 1950, Mayas y Quiches in 1966, the central provinces in 1967 and the northern region in 1912.

In the central region large vertical and horizontal offsets have been observed. The most likely regions for study appear to be the Arequipa area or the region northwest of Cusco. Because of the high Q of the region the felt area is very large.

Chapter 3

Source Mechanism and Wave Propagation Arrays

3.1 INTRODUCTION

The strong earthquake ground motion experienced at a given site can be considered to be a space-time convolution of the earthquake source function with the path effect and the effect of local site conditions. This chapter deals with the design of arrays to measure source and path effects for strong ground motion.

For a large earthquake, which generates strong ground motion of crucial engineering interest, the rupture process can extend hundreds of km and may last several minutes. Both the spatial and temporal behavior of such earthquakes are at present poorly understood. Although there are hundreds of seismic stations, many of which have been in operation for decades, only a few have recorded the complete source signature in the immediate neighborhood of the faulting associated with a large ($M \geq 7$) earthquake. Many of the existing seismic stations are operated at high gain with limited dynamic range, and therefore if near the epicenter of a large earthquake will undoubtedly be saturated immediately after the first wave arrival.

In the worldwide earthquake belts there are less than a thousand strong-motion stations that have adequate timing and response to give onscale records close to large earthquakes. Most of these strong-motion stations are located in California, although California is far from being the most seismically active area in the world.

A combined analysis of the worldwide strong-motion instrument distribution and the recurrence rate of large earthquakes shows that there is a great need for systematic deployment of relatively extensive strong-motion arrays in the most seismically active areas of the world. This deployment is necessary for the engineering profession to gain adequate knowledge of various types of sources of large earthquakes within a reasonable period of time, say less than 10 years.

While the source function is one factor influencing the ground motion at a site, the material properties of the upper part of the crust, variations in layer thickness, surface topography and local site conditions combine to continuously shape the strong ground motion as waves propagate from the source. The present inadequate distribution of strong-motion instruments makes difficult if not impossible a systematic study of this path effect. This, in turn, makes it virtually impossible for design engineers to predict accurately the ground motion of a site even for a known earthquake source.

The accurate prediction of strong ground motions at various engineering sites could result in an enormous reduction of design and construction costs. One can easily visualize that the savings resulting from strong-motion array deployment might be orders of magnitude greater than its cost.

Although the precise mechanism by which strong seismic waves are generated and transmitted to a site is quite complex, it is possible to identify three principal source types:

1) Strike-slip fault with fault length as long as 1000 km

2) Low-angle subduction thrust fault with fault length as long as 1000 km

3) Dip-slip fault (thrust or normal) with moderate fault length (~50 km).

It is also possible to identify two main types of path structures:

1) Uniform layered crust with and without waveguide effects

2) Basement-Sedimentation Basin transition with significant, relatively simple lateral heterogeneities as boundaries of sedimentary basins, contacts of different upper crustal materials, deep waveguides and other more complex three-dimensional heterogeneities.

In this chapter strong-motion array designs are presented which are intended to provide data close to large earthquakes. Although the new data by themselves would fill critical gaps in the existing strong-motion data base, one must realize the much greater potential of these data. If, through detailed correlation analysis, some regularity can be found that empirically relates the observed strong ground motion to the path and the source, the results can be generalized to the prediction of strong ground motions at other sites under different conditions. The above data base can also be integrated with recent advances in near-source numerical and analytical calculations, thereby allowing the possibility of a more quantitative functional relationship between the source and path properties and the strong motion at a site. This will further increase the usefulness of the output of the proposed strong-motion instrumentation arrays.

It is realized that even for the most widely chosen sites, there is a great uncertainty of recording large earthquakes with fixed arrays within a few tens of years. To remedy this situation, it is recommended that at least one mobile array be created. This mobile array would consist of approximately 50 instruments, operated by a trained staff prepared to go into areas of the world immediately after a large earthquake. Such an "aftershock chasing" program should allow the recording of near-source strong motion of numerous M = 5 events, many M = 6 events, and perhaps one or two M = 7 events within a few years. This mobile array could also be deployed in an area where a major earthquake is anticipated.

3.2 GENERAL CONSIDERATIONS

Source Effects

At present, what is known about the dynamics of the source of an earthquake has come from observations of relatively long period waves (5-300 sec) recorded at great distances from the fault. These data provide average properties of the source, such as the fault orientation, the approximate rupture velocity, the average slip across the fault, and the total duration of the rupture process. In order to obtain information of relevance to engineers, a detailed knowledge of the short wavelength, high frequency nature of the source is needed. This can only be obtained by recording in the near-source region. The teleseismic recordings do indicate, however, that the fault slip in a large event is not a simple, smooth process, although the resolution of these details using teleseismic data is limited to tens of kilometers. It is most likely that smaller scale heterogeneities, which will be crucial for the radiation of high frequency waves also exist. Ideally, the source is described by the spatial and temporal dependence of the fault slip. The arrays proposed herein have been designed to provide as much detail as is practical about this dependence.

The arrays have been designed to answer questions such as: How fast does the fault rupture grow, how smooth is this growth, how does the acceleration vary as a function of azimuth, and is the ground motion maximum at the fault or at some distance away from the fault? Two general types of arrays are proposed for source studies. These are differentiated by their time period of operation and flexibility. One is the permanent array to be installed in areas where magnitude 7 to 8 earthquakes are expected. The spacing and the geometric patterns of such arrays are designed to resolve as much of the source details as is possible with a surface installation (unless there are many sensors at depths of several kilometers, a very expensive proposition, the gain over surface arrays is not significant). Such arrays are designed also to minimize the influence of local effects.

The other type of array for source study is a smaller mobile array that can be moved into the meizoseismal area of a major earthquake (magnitude 7 to 8) within a few days after the event. While the permanent array may have to stay in an area for many years, the mobile array can record many magnitude 6-7 aftershocks in the same time period. Thus the information return can be very high.

Path Effects

Small earthquakes and theoretical studies for impulsive inputs show that geological structure along the path and local site can introduce considerable complexities that depend on distance and period -- e.g., dispersion and interference of body and surface waves, attenuation, reverberation, focusing and defocusing, wave conversions, etc.

At present, few strong-motion stations have been placed with the direct objective of studying path effects. Also, analytical studies are limited, by and large, to relatively simple geologic structures. There is a need to understand the effects of different types of paths, e.g., a uniform crust, a large sedimentary basin, etc., and the transition effects when waves cross the boundary between different types of geologic structure. The degree of complexity that must be built into theoretical models should also be determined. Other factors such as scattering and lateral changes in waveguide properties could all contribute to the total path effects, especially at high frequencies.

The permanent network designed for source studies can be used to study path effects in the vicinity (within 20 km) of the fault, but it will be necessary to augment this network by additional instruments extending linearly to distances up to ~100 km away from the faults for significant path effects study. When there is a local effect array in the area, the extension could then provide continuous complimentary coverage to that array.

Much of the path effect study can be performed with the proposed mobile array. With earthquakes of magnitude 4 to 7, occurring either as background seismicity or aftershocks, it is possible to study many different paths and accumulate data rapidly. Although it is anticipated that nonlinear path effects are small, this array can supply data for a study of such effects.

Impulse Response Methods

For a particular site and for the case in which the possible source regions are known, it may be possible to use small earthquakes with foci distributed over the expected source regions to study path and local effects. The response for the smaller earthquakes can be used as impulse response or Green functions which may be convolved with a suitable source function for the larger earthquake, thus permitting the prediction of strong motion at the site including automatically the path and local site effects. This technique is particularly promising in situations where the path or local effects are too complex and thus difficult to represent by analytical models. Application of the technique is based on the assumption of small nonlinear local effects, although its use may be extended by appropriate correction for local nonlinear effects.

3.3 RECOMMENDED ARRAYS

To meet the above-stated data acquisition requirements and keeping in mind the limitations on available resources, an optimized array design approach is formulated. It is believed that the recommended instrument deployment will generate within a short period of time a sufficient strong-motion data base which should give engineers adequate information to evaluate the source and path effects on strong earthquake ground motion at a given site.

Permanent Source Mechanism and Path Effect Arrays

It is recommended that three types of faults be instrumented:

1. Strike-slip fault having linear dimension of many hundreds of km and capable of generating M = 8 earthquakes. A comb-shaped array is recommended consisting of approximately 100 to 200 instruments with an average spacing of about 10 km (Fig. 3.1).

2. Subduction thrust fault having linear dimension of many hundreds of km and capable of generating M = 8 earthquakes. Geographical location of the surface fault trace for this fault type (off-shore) only permits the hanging block of the fault to be instrumented. Deployment of a linear or two-dimensional narrow band array (Fig. 3.2) consisting of approximately 50 to 150 instruments of 20 km average spacing is recommended.

3. Dip-slip fault having relatively smaller linear dimensions of about 50 km and capable of generating earthquakes up to M = 7. Faults of this type are numerous and often located close to or directly under metropolitan areas, thereby posing high hazard to structures. A two-dimensional array of 2 to 10 km spacing is recommended (Fig. 3.3). One hundred instruments would be necessary to implement this array.

Mobile Array Laboratory

With the permanent arrays, there is a distinct possibility that this project may not yield the range of observations needed for a long period of time. A mobile array with about 50 portable instruments is recommended to record the strong ground motion generated by large aftershocks (M = 6 or 7) following the occurrence of giant earthquakes (M = 7 or 8). A careful preplanning of the logistics is necessary to allow sufficiently rapid deployment of this mobile array to record the largest aftershocks. The smaller aftershocks, which usually continue for years, and the magnitude 6-7 aftershocks can provide significant source information.

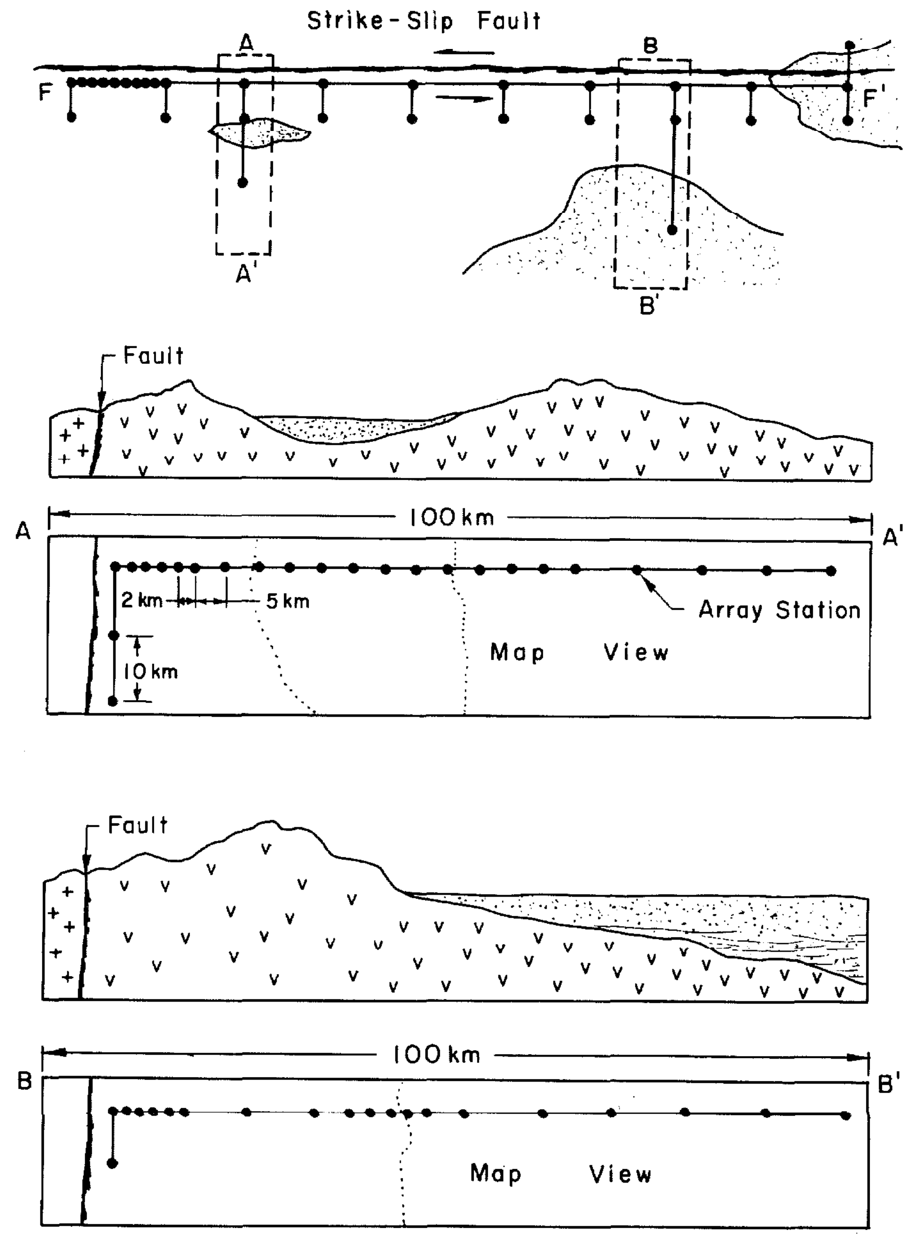


FIGURE 3.1. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY CONFIGURATION FOR STRIKE-SLIP FAULT

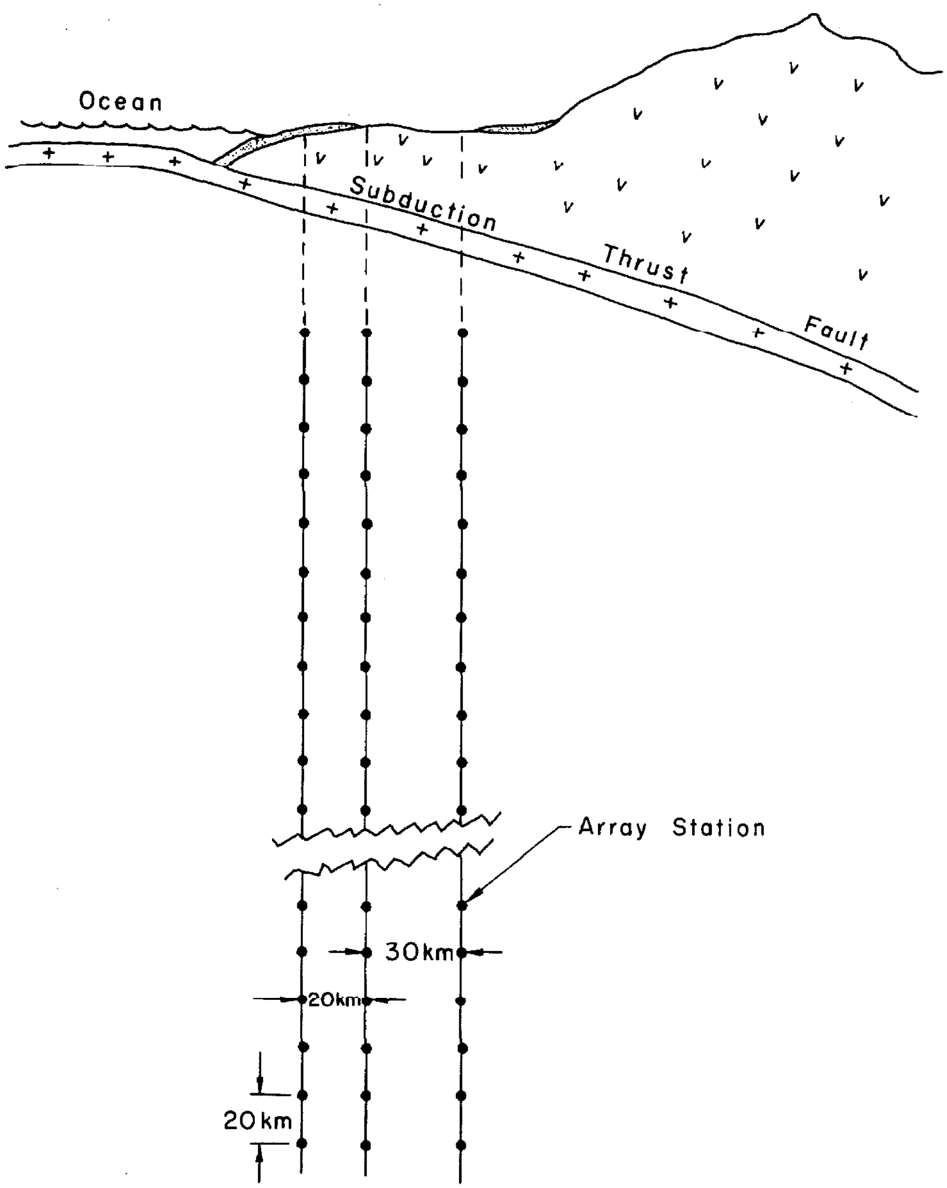


FIGURE 3.2. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY FOR SUBDUCTION THRUST FAULT

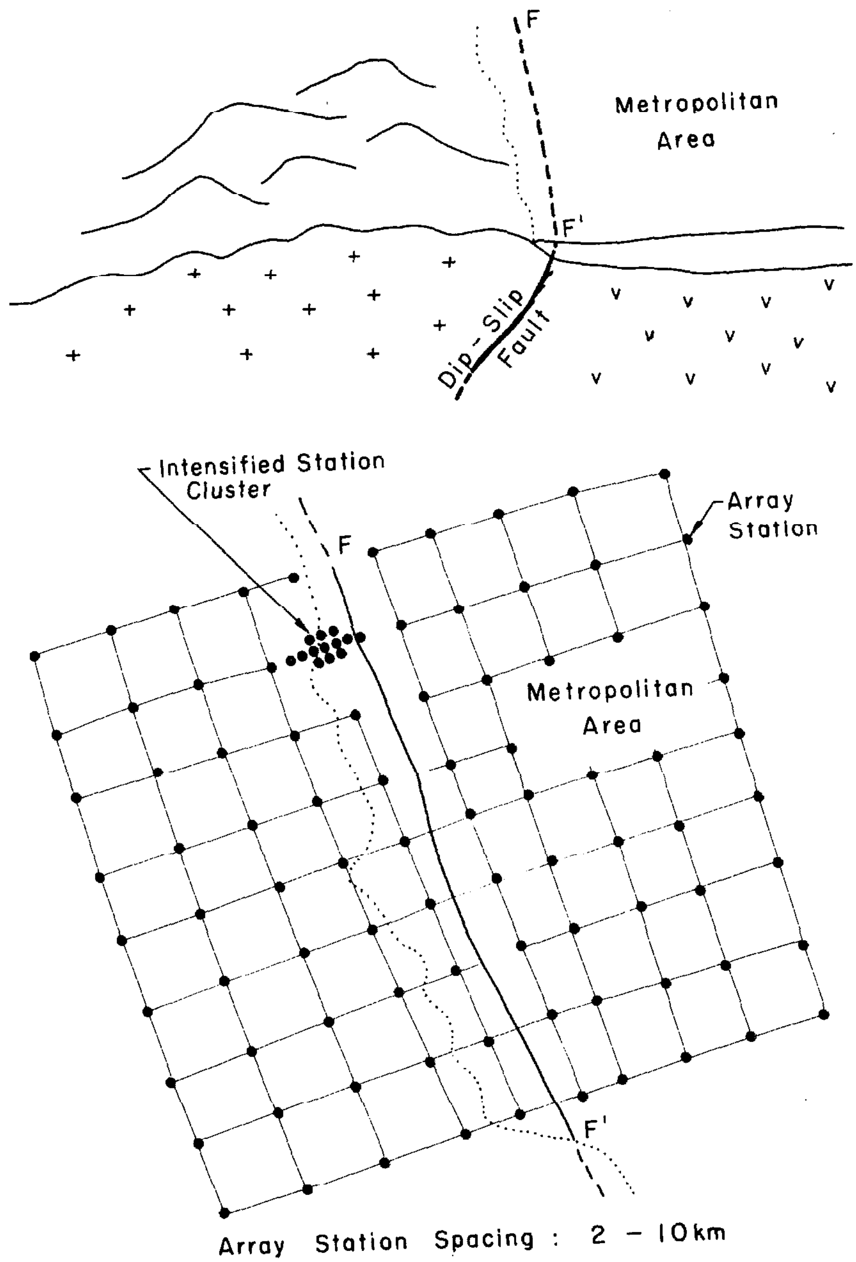


FIGURE 3.3. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY CONFIGURATION FOR DIP-SLIP FAULT

3.4 DESIGNS FOR PERMANENT SOURCE MECHANISM AND PATH EFFECTS ARRAYS

Source Mechanism Studies

Most basically, it is desired to study the source function and seismic radiation of earthquakes, that is, how the slip of a fault and the resulting radiation vary in space and time. In particular it is desired to know how this source function and radiation vary with the geologic and tectonic conditions and the magnitude, mechanism and depth of the earthquake.

Such knowledge will, for a given location, allow the prediction of the range of possible source functions. This can be used as input to a local site effect study. An example of a particular result sought is the azimuthal variability in radiated energy that can be expected from source orientation and interference patterns produced by rupture along a fault. In order to estimate this it is necessary to observe a given event at a number of different azimuths. Another important piece of information is to know the conditions under which there are multiple events in a large rupture process. Such a rupture process produces proportionately greater high frequencies than a smooth rupture.

The principles that have been followed in the design of source mechanism arrays are:

1) Every effort has been made to minimize local and propagation path effects relative to source effects by placing (when possible) the station on similar competent rock sites near the potential fault and the recording site. It is impossible to completely eliminate local and propagation path effects, or even to make these effects the same at all our recording sites. Therefore, to provide a means to check the magnitude of these effects on source mechanism data, recording sites have, in a few cases, been chosen which have different local conditions but are separated by distances small compared to the distance to the source.

2) Where possible, instruments have been placed so as to resolve the highest frequencies of interest. Also the design has been determined by the expected hypocentral depth and fault length of the potential earthquake.

Strike-Slip Fault Array

A hypothetical strike-slip fault and the array proposed to study the source mechanisms of an event on it are shown in Fig. 3.1. Although particular details of the array will vary from site to site, the characteristic dimensions and features are indicated.

In order to minimize local site and propagation path effects, the line of recording stations parallel to the fault has been placed out of the zone of crushed fault gouge on the fault itself, but as close to the fault as deemed possible. The purpose of the lines of stations perpendicular to the fault is to measure the wave decay away from the fault up to a distance comparable with the fault depth, and to aid in the relative location of any "multiple events" occurring in the main shock rupture. There are a few especially long perpendicular lines proposed to study wave propagation effects.

Most of the lines perpendicular to the fault occur on only one side because it is anticipated that radiation of events on such a fault will be symmetric about the fault strike. However, in order to estimate the effect of the local site conditions and propagation path, a few lines of stations extending across the fault have been indicated. Ideally, stations on opposite sides of the fault located at equal distances from the fault will record similar signals. Some of the stations on the lines which transverse the fault can be placed on the fault itself to find an upper limit of acceleration and to investigate the effect of fault gouge. Also indicated in Fig. 3.1 are a few sites of especially dense concentrations of stations: for example, 3-4 stations separated by 50 to 500 m. These subarrays would be used to check the coherency of higher frequency waves and to provide an estimate of the local site effects. It is recommended that the stations in these subarrays be operated in a master-slave mode to ensure a common time base.

Subduction and Dip-Slip Fault Arrays

It is proposed to study two types of faults: 1) the major offshore faults such as those found off the coast of Japan, western South America and the Aleutians and 2) the on-shore dip-slip faults such as those found in the Transverse ranges of Southern California and the Basin and Range Province of the Himalayas. The motivation for studying the latter fault type is to resolve some of the controversies which have arisen from the study of San Fernando earthquake records.

Off-shore Subduction Fault: A hypothetical off-shore subduction fault and a proposed array are shown in Fig. 3.2. Here the instrument spacing is dictated by the focal depth of damaging shallow events. Topography usually permits only a narrow and long array which may extend to more than 500 km. To capture the source characteristics of a large propagating rupture is of prime interest. If topography permits, one or two extended arms of this array may be installed perpendicular to the fault to study the decay of strong motion away from the rupture.

On-shore Dip-Slip Fault: A hypothetical fault of this type and its proposed array are shown in Fig. 3.3. The instrument placement is chosen to determine if the acceleration on the hanging wall is significantly different from that on the foot wall, and if there is significantly higher acceleration along the strike direction or along the direction of the propagating rupture of the fault. Faults of this type usually bring basin sediments in direct contact with basement rocks. An intensified station cluster (Fig. 3.3) may be set up to study the detailed effects of this transition on strong ground motion.

Path Effects Studies

One of the most important problems facing earthquake engineers is to determine the characteristics of the seismic waves generating strong ground motion for a given earthquake source. The question may be resolved for a particular site by a direct wave number analysis of data from the local laboratory type array proposed elsewhere in this report. Twenty to thirty stations spread over an area with diameter 1-2 km will be sufficient to resolve the type of incident waves and incidence angles for the frequency range of engineering interest.

The results from the Local Laboratory Array, however, may not be typical and may be difficult to apply to other sites and other sources. To find any systematic dependence of the characteristics of strong motion on the wave path, it is necessary to have an array of stations with greater areal coverage than that of a local effects laboratory array.

The problems which must be addressed are:

1) To find the wave characteristics of strong motion as a function of distance and frequency for a relatively uniform crust, for the distance range 0 to 100 km and the frequency range $0.1 < f < 30$ Hz. For example, it may be desired to study systematically the effect of an extensive low-velocity waveguide which may cause a dominance of surface waves for certain ranges of frequency and distance.

2) To find effects of relatively simple types of lateral heterogeneity on strong motion. Examples of heterogeneities are:

   a) boundaries of sedimentary basins for wave paths with various incidence angles,

   b) contacts of different upper crustal materials such as the boundary of the Gabilan range and Franciscan formation,

   c) roots of mountains such as the Andes,

   d) effects of deep waveguides such as observed in Japan and Romania for deep and intermediate earthquakes.

3) To study the effects of more complex heterogeneity, it will be necessary to compile a library of empirical impulse responses for a large number of source-receiver combinations. Such a library may be used for the synthesis of strong motion by convolving the source function with the empirical impulse response. It will be hypothesized that the impulse response representing the path-effect may be common for strong and weak motions. This assumption can be tested when necessary data become available.

In order to solve the above problems, a large amount of data from regions of various geological and topographical conditions is needed.

Herein, as a fixed permanent array for the path effects study, it is proposed to add extension legs from the source mechanism arrays (Fig. 3.1), some of them preferably connecting to the laboratory arrays designed to study local effects. These arrays will generally be linear arrays of about 10 accelerographs distributed over a distance of about 100 km. Accelerograph specifications for these arrays are the same as for the mobile array described below.

It would perhaps be difficult to acquire data necessary for a more complete study of path effects in the near future by a permanent array fixed in an area. However, necessary data may be acquired from a mobile array laboratory staffed permanently with technicians and ready for deployment in the aftershock area of earthquakes with magnitude greater than 7.

3.5 MOBILE ARRAY LABORATORY

Since the earthquakes to be studied by the mobile array may occur in an area without any local seismic network, the mobile array must have the capability of locating aftershocks with an accuracy of about 1 km. Since large aftershocks will supply valuable information on the source process, the mobile array should have the capability of source study as described in a previous section. Both capabilities are provided by the digital recorders proposed here.

It is anticipated that the extent of the aftershock area for a target earthquake would be around 100 km. For aftershock location and source study, three rows of seismographs spaced at about 10 km intervals covering the aftershock area will be required.

For a systematic study of path effects described earlier, suitable array configurations must be selected for each specific geologic and topographic condition. An aftershock zone of length about 100 km will require about 50 stations to collect data for aftershock location, source study and various path effects. The deployment and operation of an array of this magnitude will require several teams of experienced technicians.

There is no clear boundary separating path effects from local effects. In fact, instrument layout for the study of path effects must, in general, merge into arrays designed to study local effects so as to maintain observational continuity. The concept of the Mobile Array Laboratory should be equally effective as a supplement for local effects arrays when and if the situation calls for such a deployment.

The seismograph specifications for the Mobile Array Laboratory are similar to those for the permanent arrays. They are summarized in the following section.

3.6 INSTRUMENT CHARACTERISTICS

It is deemed desirable that the individual stations of the arrays described herein have a bandwidth from 0.1 to 30 Hz and a dynamic range (using gain ranging) of 10^6. The sensors should be capable of recording three components of motion linearly over this bandwidth with a maximum acceleration of 2g. (With simple modifications, a few instruments could probably be used to record as high as 5g.) Internal clocks should have a drift rate not exceeding 10^{-7}. These clocks must be able to be reset from an external, portable master clock so that the precise relative timing can be obtained periodically and especially immediately after a large event. The sample rate should be 100 Hz to allow for reliable recording of 30 Hz signals after anti-aliasing filtering. It is suggested that pre-whitening filtering be investigated. Recording time should be as long as a cassette tape would last, with 45 minutes as a minimum recording time.

The recorders should have "smart" triggers and pre-event memories of 2 sec. The trigger threshold and full-scale range should be easily adjustable to allow for studies of such things as aftershock sequences and refraction profiling. One of the primary goals of the arrays is to separate source effects from propagation path and local site effects. If the gain of all the stations in an array could be increased substantially and the trigger level lowered, teleseisms could be observed across the array as a means of estimating differences in local site effects. Routine, convincing instrument calibrations are necessary. A filter with adjustable frequency band may be needed in the trigger channel to respond to different sites with different signal and noise conditions.

3.7 ANTICIPATED RESULTS

Permanent Source Mechanism and Path Effects Arrays

The strong-motion records collected by permanent arrays will answer a number of questions of great importance in earthquake engineering and strong-motion seismology. In particular, the following results are expected:

1) Description of the effects of the type of fault or fault mechanism (strike-slip, thrust, normal) on strong motion.

2) Spatial variation of strong motion in the near source region (20 km from fault) including radiation pattern and regions in which strong motion may be intensified by constructive interference of waves emanating from a moving rupture front.

3) Classification of the rupture process as unilateral or bilateral.

4) Measurement of rupture velocity which can be used in kinematic fault models and in the testing of rupture physics models.

5) Location of multiple events or events in which abrupt changes in rupture velocity and slip velocity occur. These portions of the fault may generate most of the high frequency components of strong motion. It will be possible to correlate their location with the surficial and subsurface geology permitting generalization of the results to noninstrumented regions.

6) The records obtained in the near source region and on the legs of the permanent arrays will permit construction of reliable spatial attenuation functions which may depend on frequency and earthquake magnitude.

7) Comparison of recordings at a station for earthquakes of different magnitudes will be used to establish the degree of nonlinearity.

8) Permanent arrays will provide input information for the local effects arrays.

Mobile Arrays

The strong-motion data obtained by mobile arrays should provide needed information in the following areas:

1) Evaluation of the wave content of ground motion, i.e. relative importance of body and surface waves as a function of distance and frequency.

2) Effects of different types of surficial and subsurface geological structures on ground motion including the effects of lateral changes in structure.

3) Source information for earthquakes of lower magnitudes and for regions in which permanent arrays are impractical.

4) Evaluation of empirical Greens or impulse response functions which may be used to synthesize ground motion for larger earthquakes at particular sites.

In general, both the permanent and mobile types of arrays will provide empirical information that can be used directly in engineering design. Furthermore, detailed data so systematically gathered may be used to validate existing analytical models as well as guide the development of more complete models that govern the seismic source and propagation path effects on strong ground motions. The ultimate goal, of course, is to develop an ability to predict strong earthquake ground motion.

Chapter 4

Local Effects Arrays

4.1 INTRODUCTION

It is not possible to give a precise definition of "local effects" as considered herein in contrast to "wave propagation effects" dealt with elsewhere in this report. By one possible definition, local effects might be those which affect the components of ground motion with a frequency greater than about 1 Hz (or, alternatively, wavelengths less than 1000 m). Seismologists have tended to concentrate their attention on frequencies less than 1 Hz and there is known to be a large degree of coherence in such frequency components over local areas. In the present context, local effects refer to geologic and topographic anomalies and the manner in which they affect ground motion in the frequency ranges of concern to engineers.

In the most common specification of design ground motions for a building, no consideration is given to possible variations in ground motion over the site occupied by the building. This suffices for many practical purposes. In effect, one uses a single point specification, without consideration of gradients in the motions. However, for some special large structures (such as nuclear power plants, which may experience rocking and twisting input) and for extended structures (such as bridges, dams and pipelines), it is necessary to consider differential motions between points of the earth, that is, to consider horizontal gradients in the motions. The vertical gradient can also be important for embedded structures. In addition, there are other important engineering problems for which knowledge is incomplete, including interaction between soil and structure, soil failure and the nature of very long period motions.

Single Point Specifications

There are several major needs in the area of the single point specification of strong ground motion. These include:

1) The recording of ground motions from earthquakes with magnitudes of 7.0 or greater, and the recording of ground motions within a few kilometers of earthquakes with magnitudes of 5.5 or greater. The former type of data is almost completely lacking at this time, while there is little of the latter.

2) The clarification of the effects of local soil conditions. There still are major arguments as to when soils amplify or deamplify ground motions and as to the validity of theories for predicting this effect. Other arguments concern just how motions vary near the edges of valleys and across them. The need for data in the near field of major earthquakes is especially strong.

3) The gathering of data concerning long period ground motions for engineering applications. At present there are no good data banks of such information.

Gradients in Ground Motion

Here again, several different categories of need exist. These may be grouped as follows:

1) Assessment of the validity of theories for the propagation of waves across a site. Theories have been proposed which hypothesize that ground motions sweep across sites as Love waves or Rayleigh waves. These theories imply that significant twisting or rocking motions may be introduced at the base of structures. There is at present little or no data which can be used to assess the validity of these theories.

2) Understanding the variation of ground motion with depth. This knowledge is important in defining the input to embedded structures. There are, especially in Japan, a number of instrument arrays aimed at providing this type of data. Additional such arrays are desirable, in order to increase the chances of obtaining data during very strong shaking ($a > 0.2g$).

3) Understanding the relative motion of points from 10 m to 1000 m apart in soil. Damage to extended facilities, such as bridges and pipelines, is related largely to such relative motion. Bending strains and especially axial strains are important in the design of buried pipes. Bridge piers may be significantly influenced by local rotational acceleration (rocking or twisting) of the supporting soil. Very little data of this type are available.

Soil-Structure Interaction

This phenomenon comprises two aspects: 1) the compliance of the soil beneath a structure rocking or translating relative to the supporting soil, and 2) the smoothing out of free-field motion by a rigid foundation. These parts are called inertial and kinematic interaction, respectively. Theories are available for both interaction effects, but there is a need to test these theories, particularly those for kinematic interaction.

Failure of Soil Masses

The following types of ground failure are associated with earthquake motions:

1) Liquefaction of deposits of saturated sandy soils

2) Settlement and compaction of deposits of dry or partially saturated sandy soils

3) Failures of natural slopes and embankments

4) Ruptures caused by active surface faults.

Arrays designed to study source mechanism effects will provide considerable insight concerning item 4). Measurement of ground motions within a soil slope as it begins to fail does not seem a profitable area for field investigation. Hence, only the first two items, which are very closely related, will be considered in the design of local effects arrays. While theories for predicting the relationship between ground motion and pore-pressure buildup exist and are widely used, they are quite controversial and there is an almost total lack of applicable data from actual earthquakes.

4.2 RECOMMENDATIONS FOR THE STUDY OF LOCAL EFFECTS

In light of the needs outlined above, the following recommendations are made:

1) In the vicinity of each of the sites identified in this volume - and especially in the vicinity of the six high priority sites - from 10 to 20 conventional, off-the-shelf accelerographs should be installed immediately. Later sections of this Chapter indicate how these instruments might be deployed within such regions. The number of installations may be reduced in regions where instruments already exist.

2) Within any permanent source mechanism array of the type recommended in this volume, from 10 to 30 additional instruments should be incorporated to:

   a) record the attenuation of ground motion to distances of 50 to 150 km from the fault

   b) provide data concerning the effects of local soil conditions, the variation of ground motions across valleys, relative horizontal motions between nearby points and the buildup of pore pressures within saturated sands.

   Detailed guidance and recommendations concerning the siting of these instruments are given in later sections of this Chapter.

3) A minimum of three, and preferably six, Local Laboratory Arrays should be installed at highly seismic locations throughout the world. These are complex and sophisticated arrays with 25 to 40 instruments. They may include strain gauges and rotational accelerometers. Instruments are deployed both at the surface and down to depths of 50 m to 100 m within an area of 1 km^2 or less. These arrays would be designed so as to provide detailed data concerning the manner in which ground motions propagate through sites, thereby permitting the validation of theories intended to predict local effects. These Local Laboratory Arrays are discussed in detail in a later section of this Chapter which outlines the special site conditions which are required. These arrays may be incorporated within the permanent source mechanism arrays discussed elsewhere in this volume.

4) From 10 to 20 instruments for the study of local effects should be incorporated into the plans for any Mobile Array Laboratory, for the purpose of recording variations of motion across valleys and along other baselines of about 1 km in length. These instruments would be operated in arrays of four to ten devices, to supplement information obtained by fixed local effects arrays.

4.3 TYPES OF LOCAL EFFECTS ARRAYS

A comprehensive program for the study of local effects should involve several different types of arrays, as indicated in Table 4.1. In general, there should be three levels of ground motion arrays, involving different degrees of complexity and sophistication and aimed at different objectives. In addition, there is a need for special arrays involving measurement of ground motion but aimed primarily at providing data and/or testing theories regarding specific engineering problems. Various general features of the proposed types of ground motion arrays are summarized in Table 4.2.

It is quite important that international efforts to install large scale source mechanism, wave propagation and local effects arrays not discourage national efforts to deploy simple extended arrays or coordinated systems of elemental arrays and individual instruments. These national efforts can provide valuable data while the world awaits completion of the more extensive arrays and the first data from these installations. Indeed, it is hoped that the international array program will provide technical assistance in the planning of national efforts in less developed countries and cooperation in the processing and analysis of results from national arrays. In particular, it is important that the international array program encourage and assist the immediate installation of proven strong-motion accelerographs in the vicinity of each of the high priority sites identified in this volume.

TABLE 4.1

TYPES OF LOCAL EFFECTS ARRAYS

Ground Motion Arrays

A. Local Laboratory Arrays
B. Simple Extended Arrays
C. Elemental Arrays

Special Arrays

A. Soil-Structure Interaction Arrays
B. Liquefaction Arrays

Local Laboratory Arrays

These are the most complex and sophisticated local effects arrays. They are intended to: 1) provide data concerning relative motions between points in the free field, 2) indicate the nature of wave propagation through a site, and 3) permit testing of theories for computing the propagation of waves through a site. The objective of these arrays is of both scientific and engineering interest. Such arrays form laboratories for studying the nature of near surface ground motions in detail, and may become field laboratories for the evaluation of instruments and the testing of theories concerning soil-structure interaction.

The desired characteristics of Local Laboratory Arrays are discussed in detail in Section 4.4. They are conceived as extending over horizontal distances of the order of 500 m and to depths up to about 100 m. There will be 25 to 40 instruments in each array, including instruments for recording rotation and relative motion directly as well as the more common instruments for recording linear motion at a point. Common time bases and simultaneous triggering are required. Processing of data will require sophisticated methods involving cross-correlations among records. These arrays will be located at sites with specially selected soil conditions. Inherently they are fixed (non-portable) arrays.

A primary siting requirement is that Local Laboratory Arrays receive frequent (about one/year total from all arrays) shakings of 0.05g or greater. Much of scientific and engineering value can be learned from this intensity, and the instrumentation must have adequate resolution at this level of shaking. On the other hand, the instrumentation also must record any very strong motions which might occur.

A Local Laboratory Array may exist independent of arrays that might be installed for purposes of studying source mechanisms although enough

TABLE 4.2

LOCAL EFFECTS GROUND MOTION ARRAYS

Type of Array	Objective		No. Inst.	Flexibility		Desired Intensity	
	Scien.	Data Base		Fixed	Port.	>0.05g	>0.2g
A. Local Laboratory Arrays	**	*	25-40	**		**	*
B. Simple Extended Arrays	*	**	4-12	**	**	**	**
C. Elemental and Special Arrays		**	~3	**	**		**

should be known about the general nature of the incoming motions to permit assessment of the degree to which these motions are typical.

Simple Extended Arrays

A typical example of a Simple Extended Array is a set of instruments placed across a valley to record the changes in the amplitude and nature of motion at various locations. These arrays will yield a data base on the systematic spatial variations in motion and will permit the testing of simple one-dimensional or two-dimensional theories for predicting such local variations. In general, however, the instrumentation will be inadequate to define the wave propagation through the site and to test complex theories for this effect. Simple Extended Arrays will require 6 to 12 acceleration-measuring devices, usually (but not always) with common time base and simultaneous triggering. Some studies may be accomplished using portable arrays, employing only instruments at ground surface. Others will require fixed arrays, involving some instruments located at depth. Reasonable resolution should be achieved for intensities as small as 0.05g, but good records should also be obtained for strong ground motions.

Fixed Simple Extended Arrays may be located as part of larger fixed arrays for capturing large magnitude events, or may be located by themselves in other areas where there is a high probability of large magnitude events. Section 4.5 presents examples of useful Simple Extended Arrays and gives guidelines concerning their planning and installation.

Elemental Arrays

Examples of Elemental Arrays are vertical arrays or clusters of accelerographs within a limited area (say a diameter of 100 m). These very simple arrays provide a data base concerning the degree of variation of motion with distance and depth. In the case of vertical arrays, the data may be used to test simple one-dimensional theories of ground motion amplification.

Only a few (perhaps three) instruments need be involved in each array and simultaneous triggering and a common time base are not of high priority, although in general they are desirable. These arrays, as well as single instruments, might be used to supplement basic source mechanism arrays and laboratory arrays, or may also be placed in other seismically active areas. Numerous Elemental Arrays already exist in various countries, but as yet few really strong motions (> 0.2g) have been recorded. Additional installations of Elemental Arrays would increase the rate at which such information is acquired. Section 4.6 provides guidelines concerning the deployment and use of such instrumentation.

Special Arrays

Two types of special arrays are considered herein: those intended for the study of soil-structure interaction and those dealing with pore-pressure buildup and liquefaction.

Soil-structure interaction: No special arrays for the study of soil-structure interaction are included herein within the initial plans for instrument installation. Once the Local Laboratory Arrays are in operation and have recorded a number of motions, it may be worthwhile to construct simple structures within these arrays in order to test theories for analyzing interaction effects during subsequent shakings. In addition, national groups should be encouraged to install three to five instruments in the free field around selected already-instrumented structures at convenient locations. Section 4.7 elaborates upon these recommendations.

Pore-pressure buildup and liquefaction: It is recommended that simple installations, consisting of one or two acceleration-measuring devices plus several piezometers for the measurement of pore-pressure buildup, be installed in saturated sands at several locations where the expectancy of strong ground motions is high. Priority should be given to medium to dense sands. In the longer run, consideration should be given to the installation of arrays which form field laboratories for the study of liquefaction-related phenomena during actual earthquakes. These matters are discussed in detail in Section 4.7.

4.4 LOCAL LABORATORY ARRAYS

Introduction

The conceptual basis for Local Laboratory Arrays arises from the desire to learn more about the details of the spatial distribution of the seismic excitation within a localized region. Information of this type is needed for the development and confirmation of theoretical models for free-field ground motion analyses, subsequent analysis of nonuniform conditions, and extrapolation to soil-structure interaction situations. Local Laboratory Arrays are intended to provide additional insight into other effects as well, including for example differential and rotational motions.

Local Laboratory Arrays would be located at carefully selected sites. Ideally, these arrays would be situated in such a way as to make use of data from surrounding seismological networks in order to establish the macro-scale free-field environment surrounding the local array.

Objectives

At present, it is possible to list four interrelated objectives of the Local Laboratory Arrays. These are:

1) To measure detailed ground motions over an extensive local zone. Data of this type are desired in the formulation and confirmation of theoretical models which can accommodate seismic wave inputs of various types, frequencies, directions and phasing.

2) To determine the relative motions over the region of the array, specifically such quantities as relative displacement, strain (longitudinal and shearing) and rotational motion (torsional and rocking). These types of motion should be obtained for varying base lengths and also at localized instrument stations to the extent possible.

3) To secure acceleration data that will be of direct and immediate use in earthquake engineering design as a supplement to existing data. Such information would be additionally valuable in that comparative data will be obtained from relatively closely spaced instruments at the surface and at depth.

4) To permit the deployment of newly developed instruments for experimental purposes, i.e. to serve as a testing laboratory to the extent possible.

In order to achieve these objectives the dimensions of a Local Laboratory Array should be of the order of 500 m to 1 km in plan and depth.

Number of Arrays

It is recommended that a minimum goal be three Local Laboratory Arrays possibly in different parts of the world. The establishment of such arrays, in view of their cost, implies a long-term commitment to operation and maintenance, as well as data reduction and dissemination.

An upper limit would seem to be about six such arrays distributed throughout the world. It would be desirable to have some arrays not as permanent as others to enable a shifting of some to better sites as prediction capabilities and general knowledge of seismic sources and attenuation characteristics improve.

Siting

One requirement for siting is that geology and geotechnical properties of the site and its surrounding environs be well known and simple. The latter requirement is important if analysis of the site is to be possible.

Another requirement is that, in so far as possible, the sites should be "typical" so that data obtained can be employed elsewhere by inference. In meeting this goal it is suggested that at least two of the sites have the following general characteristics:

1) Uniform Material -- Flat over a 2 km diameter area with uniform material to a significant depth. The value of c_s might range from 200 to 600 m/s in the upper 100 m of depth and increase with depth thereafter.

2) Soil over Rock -- Flat over at least a 2 km diameter area with a value of c_s of 200 to 500 m/s in the soil of depth 30 to 100 m. The underlying rock should have a value of c_s > 1000 m/s.

Admittedly, it may be difficult to find such ideal sites, but sites possessing these general characteristics should be sought. Special sites involving deep deposits of soft material, or rock over soil, although interesting, will not lead to information of general applicability or simple interpretation. In this connection the arrays, especially those installed initially, should avoid sites prone to significant focusing or dispersion.

The water table can be of some concern in interpreting data. For the uniform site, this level will hopefully be at a depth well below the majority of the instruments.

If possible, the sites should be in sparsely inhabited areas, and certainly not encompass large structures. The desirability of studying soil-structure interaction suggests that instrumented major structures located just outside the array could provide additional valuable information.

With reference to the arrays proposed for source mechanism and wave propagation studies, it is suggested that for the strike-slip and dip-slip faults the first two fixed arrays be located from about 10 km to four focal depths from the fault zone. In this way signals of at least 0.05g can be expected with some reasonable frequency and strong signals from a major earthquake should also be recorded within an acceptable time period.

If, for a single fault system, two Local Laboratory Arrays are possible, a search should be made for geologically different sites. An obvious advantage would arise if the same source mechanism produced detailed records in two different arrays. It would also be advantageous from a siting point of view if an array could be located so as to capture data from several fault systems (one close-in and one at distance).

The selected sites should be examined to be sure that, in the event of seismic activity of great interest, it will be possible to deploy portable instruments around the fixed array to help define the free-field environment surrounding the array.

Example of Local Laboratory Array

In order to provide the reader with some idea of the envisioned scope of a laboratory type array, one possible configuration involving

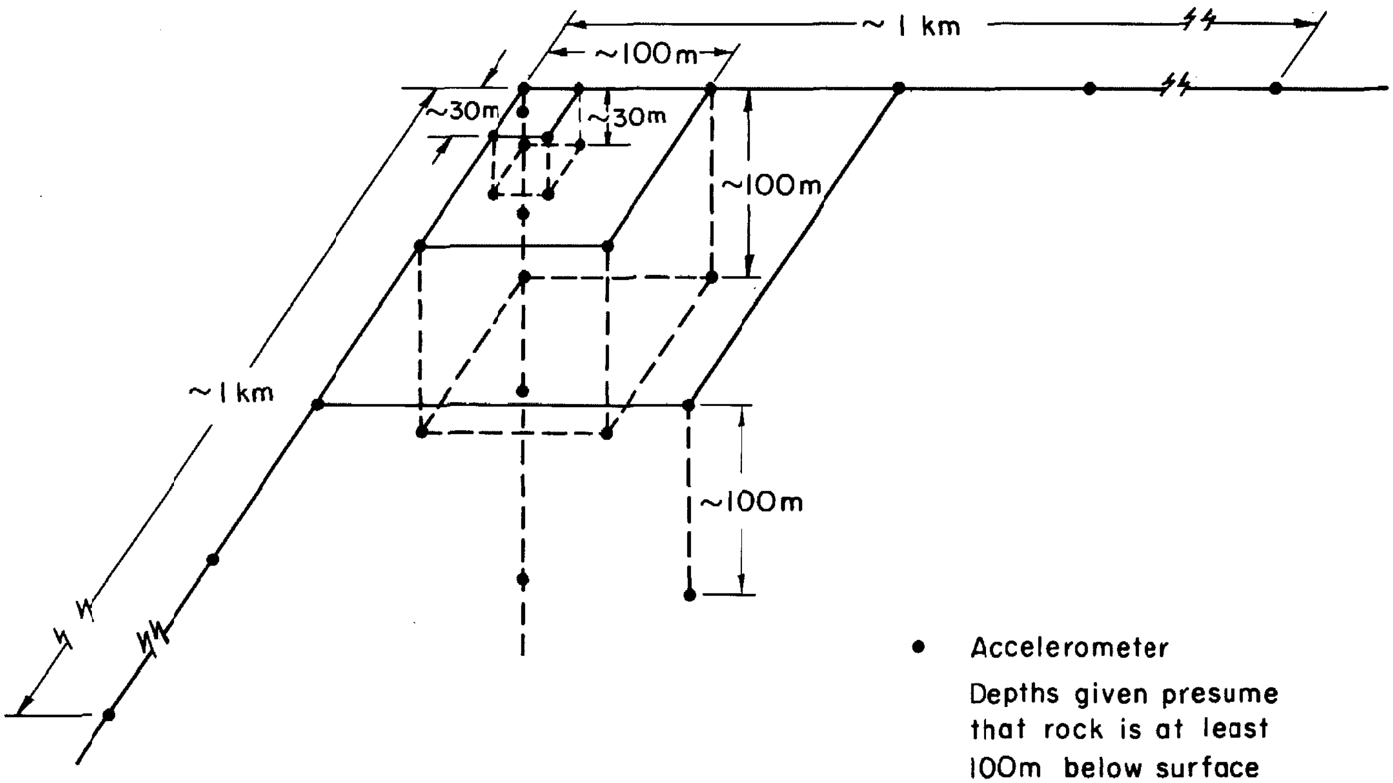


FIGURE 4.1. TYPICAL LOCAL LABORATORY ARRAY CONFIGURATION

twenty seven instruments (accelerometers, for example) is illustrated in Fig. 4.1. This particular array, covering an area of about 1 km^2, contains two orthogonal strings of instruments on the surface together with down-hole instruments arranged in box array form. The size of the array should be large enough to be representative of the site for a real facility and yet incorporate instrument spacing that will permit identification of the ground wave motions and phasing of the motions traversing the array. The latter objective can only be met if the instruments have a common time base. Other measurements of interest can also be made over the grid, such as relative displacement, strain and rotation.

The exact configuration and number of instruments in any array obviously will require careful study and planning, especially when it is realized that the incoming waves may originate from almost any direction. Indeed it may be that the array configuration should consist of concentric circles of instruments, combinations of linear and arc arrays, etc. It is recommended that both seismologists and earthquake engineers be involved in the detailed design of such arrays.

4.5 SIMPLE EXTENDED ARRAYS

Objectives

These arrays are intended for the study of the influence of local geology and topography on the earthquake motions at different locations. Efforts should be devoted to the definition of individual motions as well as to the determination of relative motions or strains. Three-component instruments, measuring two horizontal and one vertical component of acceleration, are considered in the array schemes proposed herein. However, use of rotational-component instruments should be encouraged, as this would provide additional information of significance in engineering applications.

Many arrays already exist or are planned for the observation of soil amplification effects in horizontally stratified formations (most of them in Japan). Hence, it is felt that no additional arrays need be constructed for this purpose. On the other hand, very few arrays exist for the study of the influence of valleys, surface topography and other local inhomogeneities. Herein attention will be focused on these areas.

Because a main purpose of the effort will be the calibration of simplified engineering models, a few typical configurations are chosen. Although the objective is to consider conditions more general than the stratified formations described above, simplicity will be preserved at this stage. Situations including very pronounced irregularities, such as local faults, have been excluded from consideration.

The final aim of the installation of Simple Extended Arrays is the establishment of criteria to estimate response spectra for practical design applications.

Value of Data

Experience has shown the influence of irregular geologic and topographic configurations on the local distribution of intensities and damage through focusing, resonance, edge and other effects. The usefulness of the data stems from the possibility of interpreting past observations concerning spatial distributions of intensity and damage, and of establishing conditions under which different models can be applied to predict intensity, assuming estimates are available for the value this variable would have at the site under standard conditions (firm ground, flat topography).

Although the engineers' interest is usually focused on high intensity motions, recording and analysis of low intensity events should be relevant, as a substantial number of records may be required to calibrate engineering models in the linear range of soil behavior. Some degree of extrapolation will probably be required to predict local effects for stronger motions, and that extrapolation should be based on the conceptual models of two-dimensional or three-dimensional response. It should account for nonlinear behavior and not be limited, as has been the previous tradition, to straightforward adoption of amplification functions determined under low strain conditions.

Typical Geologic and Topographic Conditions Requiring Study

Study of the geologic and topographic conditions shown in Fig. 4.2 is thought to be a good first stage for the generation of a data bank as well as for the formulation and calibration of the next generation of engineering models. Selection of sites including flat topography contiguous to one or more of the other conditions would be advantageous from cost and efficiency viewpoints.

Array Configurations

Typical array configurations are depicted in Figs. 4.3-4.6. Figures 4.3 and 4.4 correspond to narrow and wide valleys, respectively. Arrays in both cases are quite similar. Instrument R is a reference instrument located at some distance from the centerline of the valley. If possible, it might also be an element of a larger source mechanism array. Instrument C would be located at the centerline of the valley in both cases. In the wide valley, S could be a sub-array for study of local effects, its main purpose being that of providing records near the edge region. Instrument I in the wide valley would be intended for the study of the attenuation associated with edge effects.

Figure 4.5 corresponds to a hill or promontory. Here again, R is a reference instrument, located away from the base of the hill. Theoretical studies suggest that motion corresponding to standard conditions is amplified at C and attenuated at A.

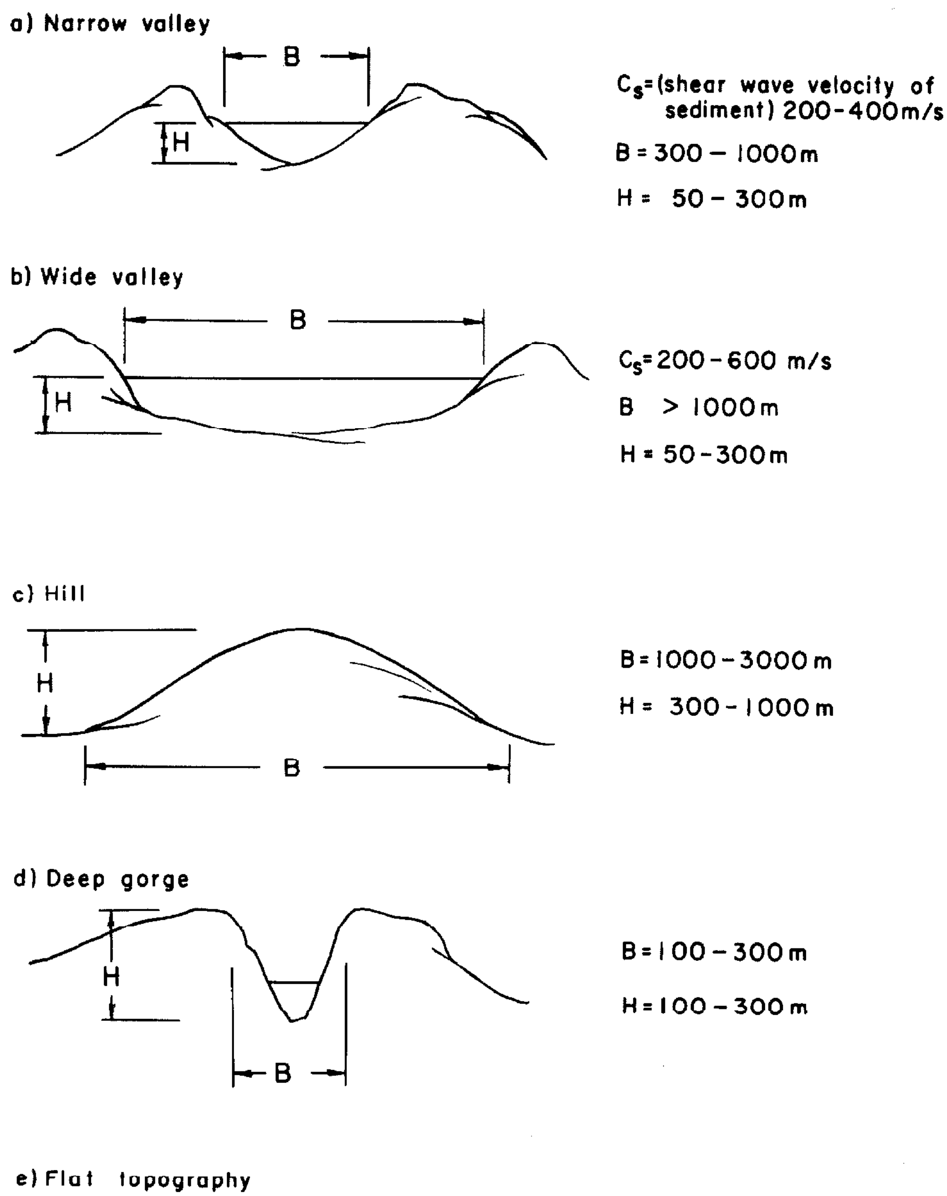
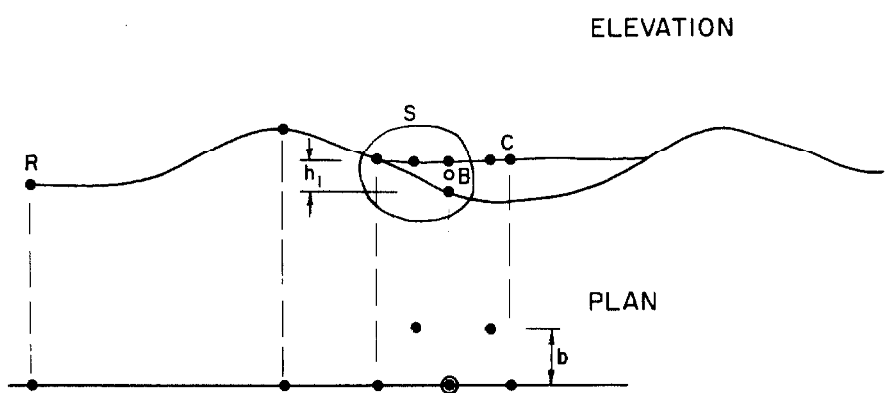


FIGURE 4.2. GEOLOGIC AND TOPOGRAPHIC CONDITIONS FOR SIMPLE EXTENDED ARRAYS



- ● Surface instrument
- o Down-hole instrument
- R Reference instrument (If possible, an element of a larger scale array)
- S Sub-array for study of edge effects
- B Optional instrument, if response of embedded structures is of interest.
- C Instrument at center line of valley

$b, h_1 \approx C_s/4$ ($C_s = \lambda_s$ at 1 hz)

FIGURE 4.3. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATIONS FOR NARROW VALLEY

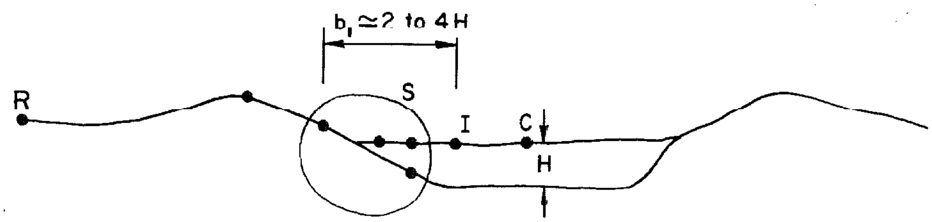


FIGURE 4.4. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR WIDE VALLEY

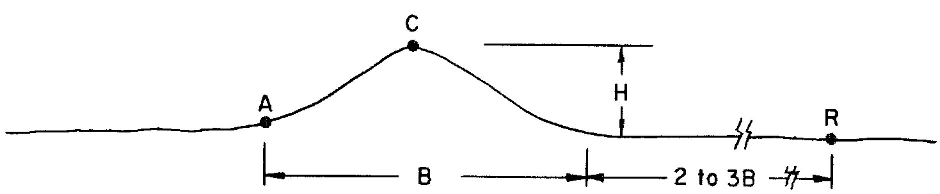


FIGURE 4.5. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR HILL OR PROMONTORY

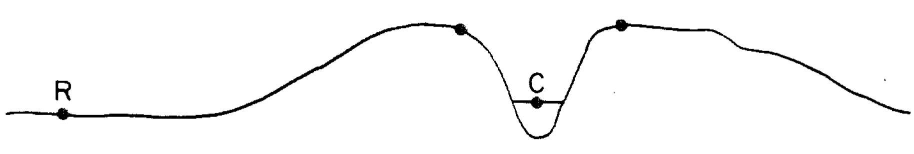


FIGURE 4.6. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR DEEP GORGE

Figure 4.6 corresponds to a deep gorge. The proposed instrumentation deployment is similar to that for a hill or promontory. The array configurations shown in Figs. 4.5 and 4.6 are minimal. Installation of one or more down-hole instruments in each case would provide very significant information for the calibration of two-dimensional models of dynamic response.

Another important case is that of linear surface arrays intended for the study of out-of-phase motions and strains for the purpose of the design of pipeline and extended-in-plan systems. Five to ten instruments are envisaged, placed along straight lines. The orientation of those lines as well as the spacing between instruments should be decided upon in terms of dominant expected wave types, their direction of propagation and their lengths for the frequencies of interest in engineering. Variable spacing might be adopted, but along at least one half wavelength that spacing should not exceed 1/8 wavelength.

Instrument Requirements

The above array configurations refer to permanent installations of commercially available strong-motion accelerographs. For most purposes, adequate resolution can be obtained with analog devices. Triggering levels should be of the order of 0.01 to 0.02g, but only those records containing accelerations greater than 0.05g are deemed to lead to sufficiently accurate spectral curves. More accurate instruments, and specifically instruments where the initial portion of each record is not lost, may be indicated for the purpose of determining relative displacements and strains.

In addition to the instruments required in the configurations described above, two or three semi-permanent instruments, of the same type as the rest, should be included in each array and eventually relocated within the array if the information obtained from initial observations makes such a change advisable.

Value of Instruments at Depth

Information obtained from down-hole instruments is significant for its own sake and for its applicability to the calibration of engineering models. In particular, such information is valuable for the following reasons:

1) The variability of motion on bedrock over relatively small distances is important for the design of many extended-in-plan structures.

2) The design of some embedded structures is based on amplitude and frequency content descriptions of motions at various depths.

3) Knowledge of simultaneous motion at and below the surface can be used to suggest models for general patterns of wave propagation in the vicinity of the site, and serve to calibrate existing and new models.

Wherever practical down-hole instruments should be added to local effects arrays.

Processing and Analysis of Data

Data obtained from Simple Extended Arrays may be used in the following manners:

1) As a source of direct knowledge on the distribution of motion for different configurations. The distribution may be expressed in terms of the comparison of spectral functions as well as of cross-correlation functions of accelerations.

2) As a basis for calibrating existing models, for improving them or for developing new ones. Calibration of simplified two- and three-dimensional wave propagation, finite element and absorbing boundary models, is foreseen as a natural outcome of the arrays output.

Common Triggering and Time Basis

Because knowledge of arrival times and phase differences would be of significance in the analysis schemes described above, it is recommended that all instruments be equipped with appropriate devices to provide a common time base. Moreover, they should operate in a master-slave mode, with the master being the most easily triggered instrument.

Interfacing with Larger Scale Arrays

The influence of local conditions strongly depends on the types and directions of incoming waves. Hence, knowledge of the general pattern of energy travel from source to site is very relevant to engineering models for study of local effects. As a consequence, it is recommended that at least one of the rock-site stations of each Simple Extended Array be located away from irregularities and correspond to one station belonging to an array intended for studies of wave propagation on a larger scale.

4.6 *ELEMENTAL ARRAYS*

This section is concerned with those configurations of instruments designed to provide data on local effects but not included within Local Laboratory Arrays or Simple Extended Arrays. These Elemental Arrays are intended to answer questions of engineering significance and will be configured in different ways according to the local conditions, presence of other instruments, and technical questions to be investigated.

Two typical situations calling for the installation of Elemental Arrays are: 1) the establishment of a permanent array to measure source mechanisms for large events, and 2) measurement of significant seismic motions in an area not covered by other arrays. In the first case, the additional Elemental Arrays would be intended to supplement the data on the source mechanism with additional data on local effects of engineering importance. In the second case the additional effort would involve tying together the strong-motion instrumentation in such a way as to maximize the value of data obtained in an earthquake even though the site is outside the range of a Local Laboratory Array or a Simple Extended Array. Because such Elemental Arrays are relatively inexpensive, they can be distributed widely, and the chances of picking up useful data from strong earthquake motions is correspondingly increased.

Types of Elemental Arrays

Several types of Elemental Arrays should be developed. These include:

1) Arrays of three strong-motion accelerometers located on the ground surface in the corners of a triangle with each leg approximately 50 m long. The accelerometers must be simultaneously triggered and have common time bases. Such arrays would provide data on local wave propagation effects and local relative motions.

2) Arrays of two accelerometers in which one instrument is located on either a rock outcrop or in deep rock and the other on soil. These would provide data on soil amplification effects. Common triggering or timing would improve the quality of the theoretical interpretation of the records. Such arrays could be part of a larger array used for other purposes.

3) Strong-motion accelerometers located at depths less than 100 m in alluvium and near other surface mounted instruments that are part of a larger array. The typical case would be in conjunction with the large arrays proposed for measuring strong-motion effects near the causative fault. Such causative fault arrays would be placed on the surface, and these additional instruments would be placed at depth to measure local amplification effects.

4) Arrays of instruments located on the surface at distances of several kilometers around Local Laboratory Arrays. These would provide data on the patterns of motion travelling toward the laboratory. Common timing is essential.

5) Arrays located on or near structures. Many arrays or sets of single instruments have been installed near or on structures.

These would be much more useful if they were arranged into simple arrays with some instruments in the free field and some on the structure and with common timing and triggering.

Array Locations

The Elemental Arrays described above are relatively simple and inexpensive to install. They can be deployed with currently available technology. Nevertheless they would provide highly useful data on local wave propagation and focusing effects that are the subjects of much concern and controversy in earthquake engineering.

Some twenty eight areas have been identified in this report as likely to experience strong shaking in a decade of observation. While decisions are being made about where to install the large expensive arrays such as those required for source mechanism and wave propagation studies, and while funding and approvals are being sought, small Elemental Arrays should be installed in as many of the likely areas as possible.

Elemental Arrays should also be located around the site of any Local Laboratory Array. They should be associated with and be supplementary to the arrays established to observe source mechanisms. Existing strong-motion instrumentation could be effectively supplemented by Elemental Arrays.

Instrument and Other Requirements

In general, Elemental Arrays should consist of commercially available strong-motion accelerometers. They may require provisions for common timing or triggering so that patterns of wave motions or coherence can be observed. Some special purpose instruments or instruments that are at this time still under development may be deployed along with these arrays, but the basic constituents of the arrays must be dependable, proven devices.

In order to obtain data on relative motion between points it would be highly desirable if accelerometer records could be differenced electronically and the differential record output on tape.

The geological and geotechnical characteristics of the site should preferably be known before the instruments are installed. When the array is associated with structures, the dynamic characteristics of the structures, as well as the engineering plans, should also be available before the instruments are installed.

Sponsorship

Elemental Arrays could be installed under a variety of sponsoring arrangements. Where Local Laboratory or Source Mechanism Arrays are installed, the complementary Elemental Arrays should be included in the plans and in the funding. Some other arrays could be developed as part of a national or local program of strong-motion instrumentation. The latter situation involves essentially making the strong-motion instrumentation more useful by tying the instruments together and planning their location.

4.7 SPECIAL ARRAYS

Soil-Structure Interaction

One example of the value and practical application of information obtained from a Local Laboratory Array is a quantitative understanding of typical soil-structure interaction phenomena. Records obtained from this type of array as a result of one or more sizable earthquakes would establish the precise field of motion expected at the site for subsequent earthquakes. Typical simple structures could then be constructed within the array site, appropriately instrumented and observed during later earthquakes.

Interpretations of the extensive data base obtained from the envisioned soil-structure interaction experiments along with confirmatory theoretical analyses are expected to identify simple free-field arrays (perhaps one instrument) and essential structural arrays (perhaps one or two instruments) actually required for practical interaction of situations. This knowledge could then be applied to the instrumentation of a number of real structures in high seismicity areas of the world, along with free-field instruments if necessary, in order to gather a meaningful collection of data on the earthquake response of existing structures. The structures used in such studies should have clearly defined properties so that their response behavior can be easily interpreted.

Three structural types are considered as possible test beds for Soil-Structure Interaction Arrays: 1) A prototype rigid foundation of low mass, 2) a one-tenth scale simple structure with a rigid foundation and a massive superstructure, and 3) an extended linear structure buried in soil.

Prototype rigid foundation: This could be a rigid reinforced concrete box or cylinder about 40 meters in plan and embedded in soil to a depth of some 20 meters. The box should have the same translational and rotational inertia as the displaced soil. Instrumental arrays attached to the prototype should include:

1) Translational and rotational accelerometers of the same type as used in the Local Laboratory Arrays (four instruments)

2) Extensometer probes extending into and anchored to the soil along the soil-structure interface area (20 instruments).

Model structure: The 1/10th scale model structure should have a simple shape and be placed directly on the soil surface as indicated in Fig. 4.7. Instruments attached to the model structure would include:

1) Translational and rotational accelerometers on the rigid foundation and massive superstructure (four instruments)

2) Dynamic strain gauges on structural elements (24 instruments)

3) Dynamic earth-pressure meters under the rigid foundation (four instruments).

Extended linear structure: The extended linear structure could be a continuous thick-walled steel pipe, buried in a horizontal plane through a Local Laboratory Array and so oriented as to maximize the differential motion of the pipe as the wave passes the linear structure. The pipe should be proportioned to provide significant bending and shear stiffness contrasts between the surrounding soil and the pipe. The pipe should be provided with interior strain gauges (about 40) and exterior extensometers (about 20). In addition to these instruments, a number of accelerometers (about 10) should be installed along the length of the pipe to measure wave propagation along the pipe and to assess the attenuation of free-field motion due to the presence of the pipe.

Data processing: All accelerometers, extensometers, strain gauges, and earth pressure meters for soil-structure interaction studies should have the same sensitivity, resolution and recording requirements as the Local Laboratory Array instruments. Data reduction and processing should also be the same.

Liquefaction and Related Phenomena

The primary purpose of the proposed arrays is to obtain accelerations and pore-pressure histories at suitable locations within deposits of saturated or partially saturated soils, especially medium and dense sands.

Two levels of array sophistication appear to be useful for the study of *in situ* liquefaction phenomena. The first level would provide basic information at minimum cost and array complexity. This array level could be easily sited with a minimum program of local soil investigation. The second level of array sophistication is more desirable but requires greater complexity and expense, more site investigations, and is applicable to sites having particular geological characteristics.

Small liquefaction arrays: The simplest array for *in situ* liquefaction studies would consist of one or two strong-motion accelerometers and one or two piezometers placed at different depths in the same borehole. One of the accelerometers would be anchored at the ground surface and the piezometer(s) placed in a sealed borehole. Simultaneous records

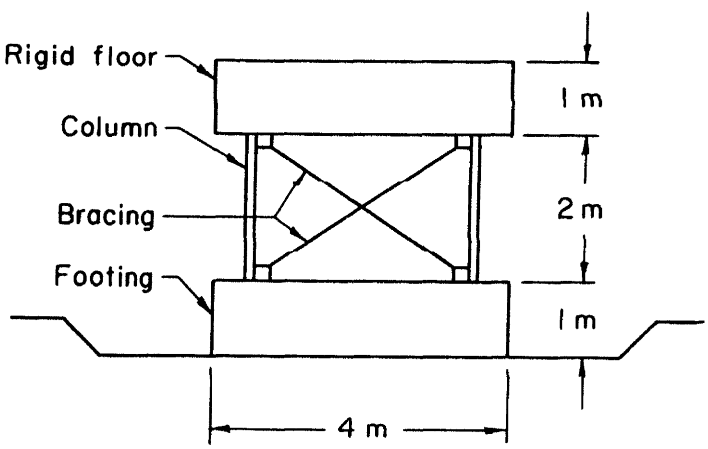


FIGURE 4.7. BASIC STRUCTURE FOR INTERACTION STUDIES

of the time histories of pore pressures and the ground surface acceleration should be made.

Small liquefaction arrays should be sited in a geologic environment that includes a saturated sand stratum at least three meters in thickness and located at a depth of no more than 15 m. The priorities of sand densities in the stratum to be instrumented are: 1) medium, 2) medium to dense, and 3) loose to medium. Loose sands should be avoided because of the risk that ground failure and sand boils would disrupt the instrumentation. The minimum strong-motion surface acceleration potentials for this type array should be 0.10 to 0.15g for sands of medium density, more than 0.20g for medium to dense sands and 0.05 to 0.10g for loose to medium sands.

Research liquefaction arrays: Whereas most people today recognize that current field tests, laboratory procedures, and numerical and analytical techniques are able to identify the danger of liquefaction for loose deposits, great uncertainties exist for the case of medium and dense sands. This situation and the somewhat conflicting views existing on this issue have favored the adoption of strongly conservative design approaches to the problem, with economic implications that can be particularly significant in large scale projects. Since experience has shown that laboratory tests results are doubtful and can be made to fit quite different theories, it is felt that a decisive step can only be achieved by direct *in situ* observations. The envisaged special arrays would help to gain a better understanding of:

1) The correlation between liquefaction potential and *in situ* geotechnical properties (e.g., penetration resistance, stratigraphy, grain size distribution, etc.) of a given sandy soil;

2) The process of spatial diffusion of liquefaction as a function of the soil geotechnical properties and stratographic configuration and the largest depth at which liquefaction can occur in a given deposit;

3) The correlation between pore pressure and acceleration histories, the latter being the key variable used in liquefaction analyses;

4) The development and dissipation of earthquake induced pore pressures in a given deposit from a three-dimensional viewpoint.

5) The validity of theories for predicting the generation of excess pore pressure and its dissipation after the end of ground motion, with related drainage path effects.

It is anticipated that the interpretation of a few sets of records from a well located array might bring about significant changes in current methods for assessing the likelihood of liquefaction.

Research liquefaction arrays would consist of a number of boreholes with several instruments each. A possible arrangement is shown in Fig. 4.8. Since maximum liquefaction depths are of the order of

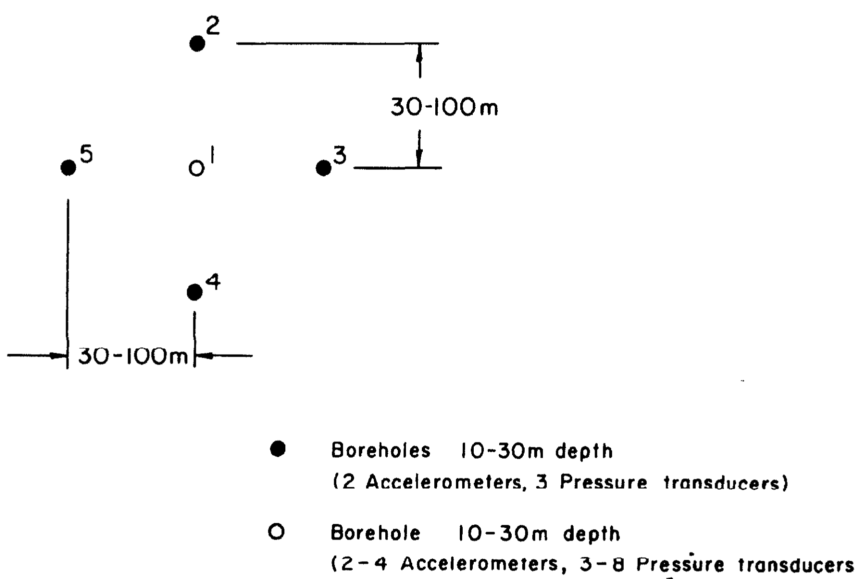


FIGURE 4.8. TYPICAL RESEARCH LIQUEFACTION ARRAY CONFIGURATION

20-30 m, the depth of the boreholes should typically span between 10 and 30 m; the bottom of the boreholes roughly coinciding with the lower boundary of the potentially liquefiable soil formation. Each of the peripheral boreholes of such an array (Nos. 2 to 5) should carry two accelerometers (one at the top and one at the bottom), and perhaps three pore-pressure transducers (two at the same points as the accelerometers and one at mid-depth). The central borehole should carry one or two additional pore-pressure/accelerometer packages at intermediate points (typical spacings of 3 to 6 m) in order to monitor in greater detail time histories as a function of depth.

All of the instruments in a research liquefaction array should have a common time base, chiefly in order to allow correlation of pore-pressure histories at different boreholes and pore-pressure and acceleration histories at the same borehole. Operation in a master-slave mode should be envisaged, with one of the surface accelerometers acting as a master or reference instrument.

Priority in site selection should be given to extended (~1-2 km^2) deposits of saturated, sandy soils, possibly with significant trends of variation of average densities in the horizontal direction. Ideally this should permit placing one array at a location having medium sands, one at a location having dense sands, and perhaps one where loose sands are present. Consideration should also be given to large scale deposits (tens of km^2) in the vicinity of active seismic sources, where several arrays could be installed in order to monitor dynamic pore pressure phenomena both as a function of focal distance and local geotechnical properties. Correlation between data from different liquefaction arrays could be provided by their having a common absolute time base.

Because of their characteristics, these research liquefaction arrays can only be intended as permanent installations. It is also evident that an adequate site selection requires relatively careful geotechnical exploration. A reasonably detailed stratigraphic description is needed, together with determination of standard (or equivalent) penetration resistance and grain size distribution as close as possible to the instrument locations. Permeability tests would also prove valuable. Careful monitoring of water table level is important.

Instrument characteristics: As it is desirable to obtain data over a large range of ground shaking intensities, say from 0.02g to several tenths of a g, use of force-balance acceleration transducers is suggested. The same type of sensor should be employed at both the surface and down-hole locations. Flat frequency response up to 25-30 Hz is required.

Strain gauge type pressure cells and pieze-resistive pressure devices are available for dynamic pore pressure measurements. Some development work is anticipated in order to couple such sensing units with strong-motion recording units. The overall frequency response of the pore-pressure instrumentation should be comparable to that of the accelerometers. Valuable information on the characteristics and anticipated performance of pore-pressure devices has been obtained in connection with the Rio Blanco underground nuclear test. Special care is required for impedance-matching aspects in the down-hole installation of these units.

Analog recording systems are considered adequate, provided an overall dynamic range of 50-60 dB can be attained. However, more study appears necessary to better define this aspect of the problem.

Analysis and interpretation of data: In seismic pore-pressure histories it could be useful to look separately at the "sustained" increase-decrease trend, and at the superimposed high frequency signal. Hence, adequate provisions should be made for standard bandpass filtering to separate the sustained component. Typical sampling rates of 100 samples/sec appear adequate for most applications, both as regards acceleration and pore-pressure signals. The need for performing relatively sophisticated analyses such as cross-correlations between signals recorded at different points is anticipated. Other processing techniques are likely to evolve from specific studies, as data of this type become available.

Useful information on the correlation between, for example, peak ground acceleration and peak excess pore pressure can be obtained starting from shaking levels as low as 0.05g and less than ten significant cycles of motion. Hence, location of the proposed special arrays should give priority to sites where there is frequent occurrence of events in the 0.05-0.10g acceleration range, and relatively high probability of accelerations greater than 0.2g in the near future.

Interfacing with other arrays: Efforts should be made to locate all liquefaction arrays as close as possible to accelerometer stations which are on competent ground (rock, firm soil) and which belong to a larger-scale array devoted either to regional wave propagation studies or to source mechanism studies. The source mechanism array seems to be more promising because experience has shown that the chances that significant pore-pressure phenomena will occur are very high whenever deposits of saturated sandy soils are present within the epicentral area of a strong earthquake. Furthermore, sites near the epicenter will experience the strongest shaking and, hence, the greatest potential for development of excess pore pressures. A detailed knowledge of the patterns of motion inputed to the soil will improve the understanding of the phenomena involved in cyclic loading. Data on the behavior of the soil could be useful to studies of seismic wave propagation as well.

4.8 DEPLOYMENT CONSIDERATIONS

This section discusses the possible composition of a total package of instruments for measuring local effects. Two levels of installation are considered:

Level I: An optimum level, representing an appropriate balance between effectiveness and cost.

Level II: A minimum level, below which the effectiveness of the installation would fall off sharply.

The particular configurations presented are illustrations only; actual details must be chosen to fit the particular situation. The use of portable arrays is also discussed.

Local Effects Instrumentation as Part of Source Mechanism Arrays

The source mechanism arrays discussed elsewhere in this volume are intended to record the very strong motions near (within 20 km) the fault break associated with large earthquakes. Most of the instruments in such arrays will be sited on rock. These arrays should by themselves yield data which earthquake engineers have long desired. At the same time, the opportunity to obtain other much needed data should not be overlooked. The following guidelines should be considered:

1) For magnitudes greater than 7.0, and especially greater than 7.5, there is a need to measure strong motions to distances greater than 20 km from the fault. Additional instruments should therefore be placed along lines extending out from the fault to a considerable distance. Data from these additional instruments, together with those from the instruments in the basic array, will permit greater accuracy in the measurement of attenuation relations. Simultaneous triggering of the additional instruments is not necessary.

2) In conjunction with some of the source mechanism instruments installed on rock, additional instruments should be placed nearby on soil to provide data as to how soil modifies really strong motions. Priority should be given to sites located closest to the fault, and spaced along the fault.

3) Several Simple Extended Arrays should be placed in connection with source mechanism array instruments installed on rock. They will give important data concerning horizontal variation of ground motions across different formations, at strong motion levels.

4) Other instruments should be installed in cities within 50 km of the fault containing significant engineered structures, and near selected special structures such as large dams. In addition, one or more Local Laboratory Arrays and several liquefaction arrays should in general be included.

Table 4.3 indicates the instrumentation which should be added to a typical source mechanism array for the sake of collecting data concerning local effects. Table 4.4 suggests the deployment for the instruments comprising the Elemental Array category. Note that no research liquefaction arrays are included, primarily because more planning and research is required for the design of such arrays. It is, however, recommended that such arrays be installed in the future.

Strike-slip fault: Figure 4.9 illustrates the principles of deployment discussed above for a strike-slip fault mechanism. The solid points represent instruments which might be part of a source mechanism array. For purposes of studying attenuation, a string of instruments should be extended out to 150 km on each side of the fault at the mid-point of the source mechanism array. The figure illustrates possible locations for Local Laboratory Arrays, Simple Extended Arrays, and small liquefaction arrays and other instruments falling under the category of Elemental Arrays.

TABLE 4.3

LOCAL EFFECTS ARRAYS TO BE ADDED TO SOURCE MECHANISM ARRAYS

Fault type	strike-slip		subduction		dip-slip	
Level of effort	I	II	I	II	I	II
Local Laboratory Arrays						
No. of arrays	1	1	1	1	1	1
Total No. of accel.	30(15)	26(13)	30(15)	26(13)	30(15)	26(13)
Simple Extended Arrays						
No. of arrays	2	-	2	-	1	-
Total No. of accel.	12(3)	-	12(3)	-	8(2)	
Elemental Arrays						
Total No. of accel. (see Table 4.4)	20(1)	11	14(1)	10	12(1)	10
Simple Liquefaction Arrays						
No. of arrays	2	-	2	-	2	-
Total No. of accel.	2(4)	-	2(4)	-	1(2)	-
Total No. of piezo.						
Total No. of instruments	68(23)	37(13)	62(23)	36(13)	53(20)	36(13)

( ) denotes instruments placed at depth.
These numbers do not include allowances for non-functioning instruments.

TABLE 4.4

ELEMENTAL ARRAYS AND INSTRUMENTS TO BE ADDED TO SOURCE MECHANISM ARRAYS

Fault type	strike-slip		subduction		dip-slip	
Level of effort	I	II	I	II	I	II
Individual accelerographs to observe attenuation	10	5	4	4	6	4
Instruments on soil in conjunction with source mechanism array instrument on rock	4(1)	3	4(1)	3	3(1)	3
Individual accelerographs near engineered structures	6	3	6	3	3	3
Total No. of instruments	20(1)	11	14(1)	10	12(1)	10

( ) denotes instruments placed at depth.
These numbers do not include allowance for non-functioning instruments.

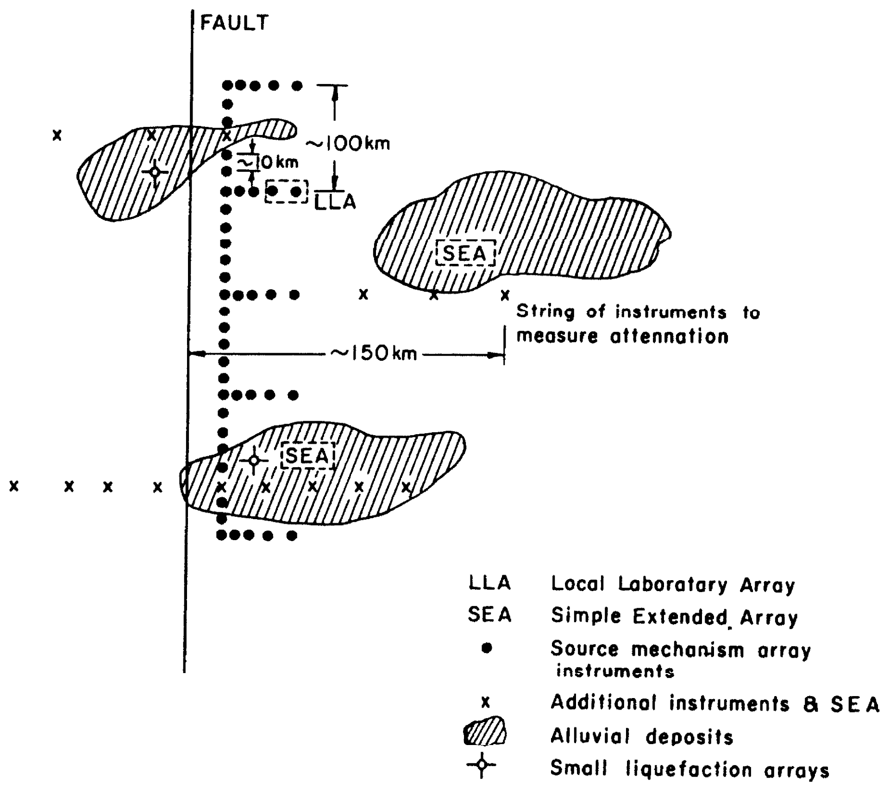


FIGURE 4.9. DEPLOYMENT OF LOCAL EFFECTS ARRAYS WITH SOURCE MECHANISM ARRAY FOR A STRIKE-SLIP FAULT

Subduction faults: The same general deployment strategy outlined above applies for subduction faults, except that in general no instruments would go on the submerged side of the fault. If, in the future, satisfactory instrumentation for submerged operations is developed, it would be desirable to add such devices to either then-existing or still planned arrays.

Dip-slip faults: The configuration of source mechanism arrays for dip-slip faults about 50 km long is sufficiently different from those proposed for long strike-slip faults or subduction zones that the Simple Extended Arrays and Elemental Arrays associated with the source mechanism array should also be different. In this case the source mechanism array will be a grid some 50 km on a side. This should provide a fairly good picture of the attenuation phenomena on rock. Additional arrays should consist of:

1) Instruments or Elemental Arrays located 50 and 100 km from the fault to provide data on attenuation beyond the source mechanism array. These should be on both sides of the fault.

2) Instruments or Elemental Arrays located on soil within the source mechanism array.

3) One Simple Extended Array at an appropriate valley or alluvial site.

4) One Simple Liquefaction Array.

It may also be desirable to locate a Local Laboratory Array within the source mechanism array, but this depends on local geology and site conditions. Figure 4.10 shows a typical configuration.

Local Effects Measurements Independent of Source Mechanism Arrays

Because of the complexity and expense of installing and maintaining source mechanism and wave propagation arrays, such arrays will be uncommon. Strong motions will occur in many areas of substantial seismic risk that are not covered by such intensive instrument arrays, and data from these events could be captured by deploying Simple Extended Arrays and Elemental Arrays in these areas. Furthermore, local and national authorities may wish to install these simpler arrays as a means of improving local earthquake engineering design practice. With international cooperation, the design of these arrays could be improved and the information exchanged. Details of the deployment of such arrays will vary from location to location.

Minimum installation: A minimum deployment plan would consist of approximately 20 standard accelerographs installed in the vicinity of each of the 28 promising sites identified in this volume. These instruments might be deployed as suggested in Figure 4.11. A given installation would include (see Table 4.5):

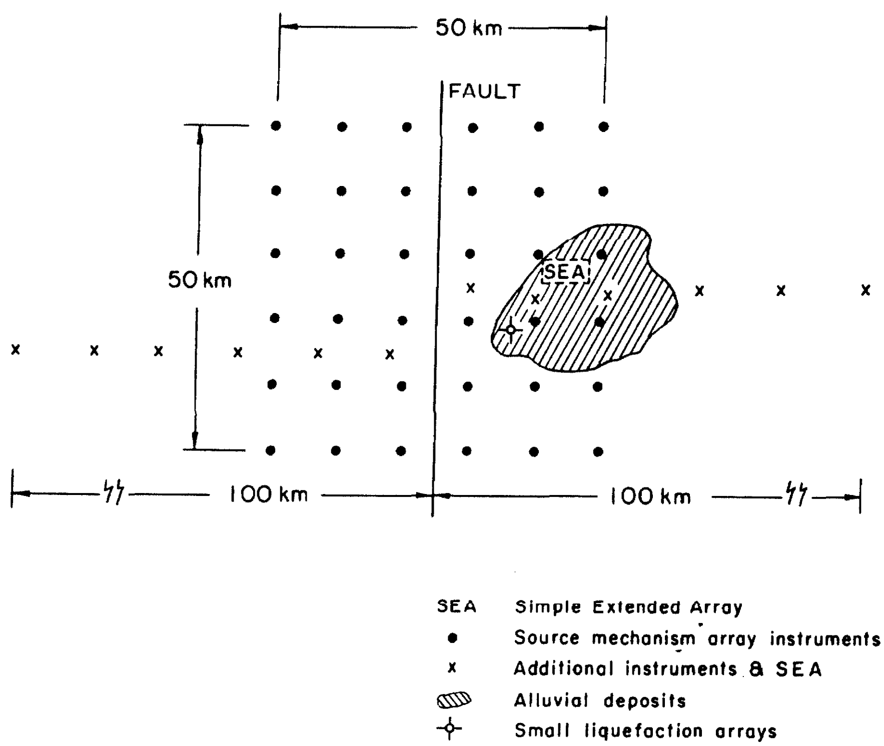


FIGURE 4.10. DEPLOYMENT OF LOCAL EFFECTS ARRAYS WITH SOURCE MECHANISM ARRAY FOR DIP-SLIP FAULT

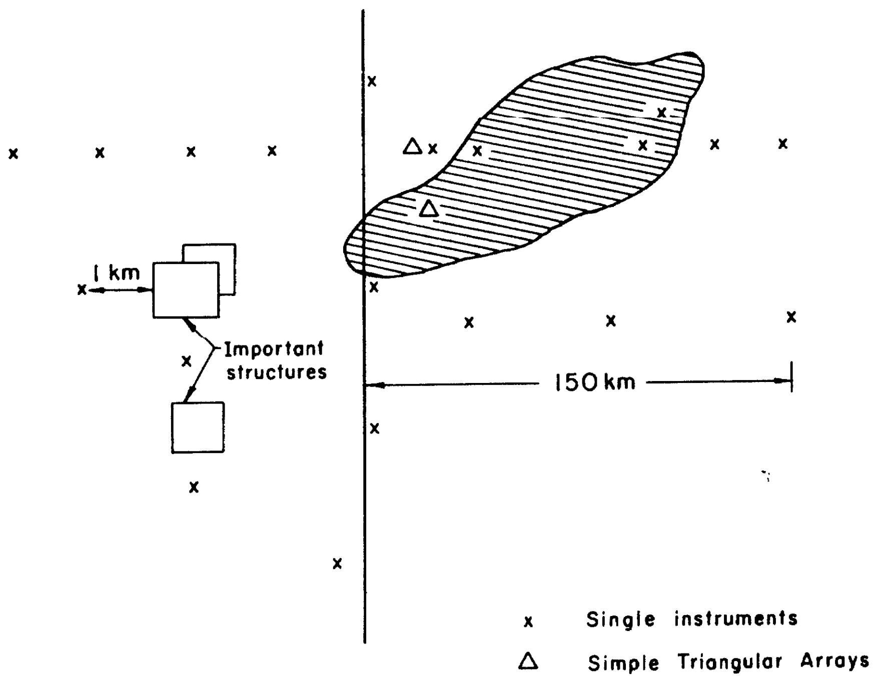


FIGURE 4.11. MINIMUM INSTALLATION FOR STAND-ALONE LOCAL EFFECTS ARRAYS

TABLE 4.5

LOCAL EFFECTS INSTRUMENTATION FOR FAULTS
WITHOUT SOURCE MECHANISM ARRAYS

NUMBER OF INSTRUMENTS REQUIRED

	Minimum Effort	Optimum Effort
Attenuation studies	10	20
Soil amplification studies	3	4
Simple Extended Array	-	8(2)
Soil-structure Interaction Array	3(3)	6(3)
Simple Liquefaction Array	-	3(2)
Elemental Arrays	6*	28(15)
Total No. of instruments	22(3)	69(22)

*Two simple triangular arrays.
( ) denotes instruments placed at depth.

1) Six instruments to record motions with distance away from the fault, so as to define attenuation relationships. These would preferably be on rock.

2) Four instruments deployed along the fault and close to it to capture any extremely large ground motions that might occur. These too would preferably be sited on rock.

3) Three instruments on soil sites adjacent to instruments on rock.

4) Three instruments located near structures of engineering interest.

5) Two or more Elemental Arrays of three units each arranged in a triangle with legs 50 m long. These should be on different geologic settings and should be sited on soil.

Improved installation: Some nations may wish to improve upon these minimum installations. The instruments of an improved installation might be deployed as suggested in Fig. 4.12. Improved installations would involve (see Table 4.5):

1) One or more sets of strong-motion accelerometers located at distances between 10 and 150 km from causative faults in order to obtain data on attenuation.

2) One or more Simple Extended Arrays for study of local wave propagation.

3) For favorable locations, one Local Laboratory Array and one small liquefaction array.

4) Instruments on or near engineered structures.

Mobile Instrument Arrays

Aftershock sequences provide unique opportunities for obtaining a number of records of motions with different magnitudes originating from a fairly localized source. Although there will certainly be some difference between the local effects observations corresponding to various magnitudes and hypocentral distances, determination of these effects at smaller intensities is still of significant value. Hence, deployment of surface arrays or portable instruments in the afterhosck area of large earthquakes is strongly recommended. Each array should include about 10-20 accelerographs. Detailed siting considerations should follow the principles stated above for permanent instrument arrays. Common triggering will in general be required, as the influence of local conditions may lead to great differences in motion intensities at different points during the same shock.

Mobile arrays will be especially valuable when deployed after a major earthquake has occurred on one of the faults instrumented by a

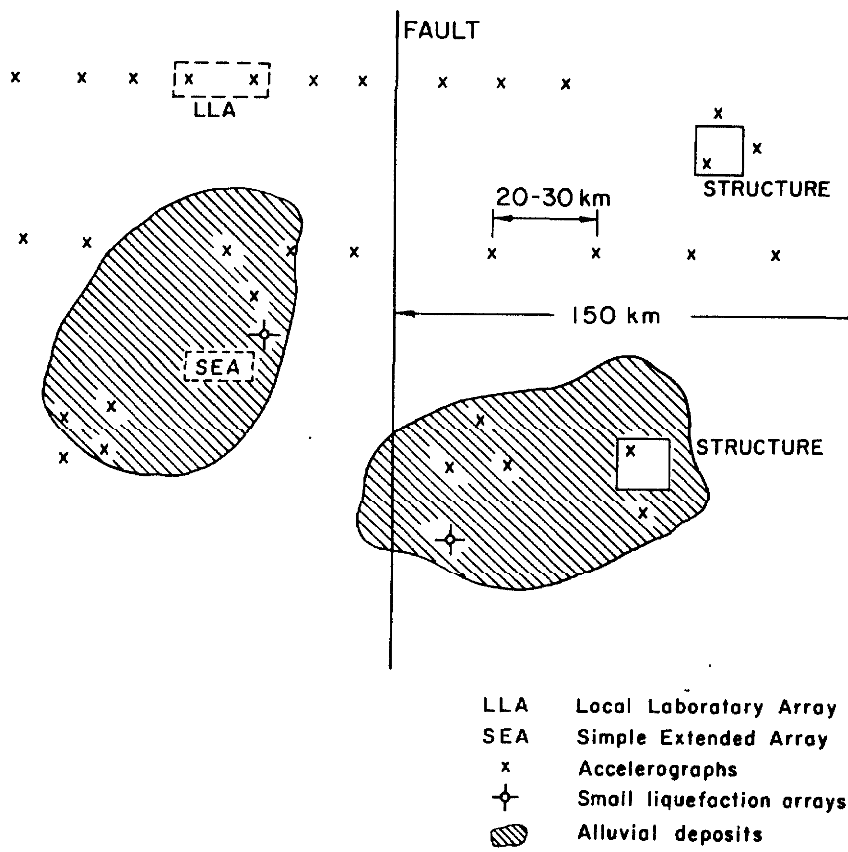


FIGURE 4.12. IMPROVED INSTALLATION FOR STAND-ALONE LOCAL EFFECTS ARRAYS

source mechanism array, and when operated in conjunction with wave propagation investigations also using mobile instruments. It is important however that some 10 to 20 instruments be specifically earmarked for local effect studies and be under the control of engineers.

Design of Data Processing and Analysis System

The design of software is as important as the design of hardware. Some stages of data processing can rely on adequately designed hardware, but advanced analytical procedures and software are needed to reach definite conclusions in particular cases. Hence, at least one standard data processing and analysis procedure should be established along with the design and specification of each array.

A standard data processing procedure should specify the following:

1) Sampling time interval

2) Characteristics of band-pass filter for pretreatment of data

3) Duration of recording or number of data points

4) Characteristics and limitations of algorithms employed for data analysis such as correlation function, power spectral density, coefficient series for auto-regressive models, etc.

5) Allowable limit on signal to noise ratio for both continuous wave and pulse type noise.

The development of software may require significant funds in addition to that for construction of the array. On the other hand, independent designs of hardware and software may cause much confusion in future use of the results of these experiments.

Chapter 5

Array Construction and Operation

5.1 INTRODUCTION

The primary factors to be considered in connection with array construction and operation are: 1) the availability of field tested instrumentation suitable for use in a program in which data are obtained infrequently over a twenty year period; 2) the cost of establishment and operation of the arrays that are desired in each region; 3) the availability of local personnel to maintain the instrumentation; and 4) the need for an organization to act as a data center to assemble the data, to process it in a standard manner, and to disseminate the data for interpretation and application.

The task has been approached by assembling information about the operation and costs involved in several large local strong-motion instrumentation programs. This information has then been utilized to estimate the costs of operation of the types of arrays that have been recommended elsewhere in this volume. In order to make comparative costs, a currently available digital accelerograph has been selected as a "basic" instrument for use in estimating the cost of planned arrays. The cost of changing to other instruments can then be readily "factored" into the overall cost figures. A "basic" array configuration has been defined for each type of array recommended. These costs subsequently have been adjusted for the situation envisioned at each of the 28 promising locations for strong-motion arrays. The cost for each location is influenced by two factors: 1) the degree of difficulty in conducting operations at different locations, and 2) the dimensions of the array that is possible compared to the "basic" array for each type. The procedure outlined is believed to allow others to make further adjustments to these estimates as may be required by more detailed evaluations of each location and type of array.

With respect to data processing and dissemination, it is recommended that three centers be established to assemble, process, and disseminate data. The most natural subdivision at present would seem to be one data center in North America, one in Asia, and one in Europe or the Middle East

5.2 STRONG-MOTION INSTRUMENTATION

The following discussion describes the specifications and costs of various types of strong-motion instrumentation that have been suggested for possible inclusion in source mechanism-wave propagation and local effect arrays throughout the world. The instrumentation falls into three classes:

1) Instruments that have been manufactured, tested, and are available on the open market.

2) Instruments requiring development. Although various components have been developed and manufactured, these have not been integrated into a single operating unit. Consequently some development and testing will be required prior to field deployment.

3) Instruments requiring design. This category of instrumentation will require a considerable design effort to produce a prototype prior to the development and testing of field units.

The costs shown for the first and second class are estimated in U.S. dollars for export at the present time. No cost estimates have been made for the instruments that require design.

Presently Available Systems

1. Accelerographs

The accelerographs described here are capable of recording three triaxial channels (or multiple of three channels) of acceleration data during strong earthquakes. Each system is triggered by motion exceeding a preset threshold level and continues to record data for the duration of the earthquake. The accelerographs have the capability of recording numerous events with incoming signals as high as 1g or greater. The instruments may be operated as single units or interconnected for simultaneous starting and timing signals; the latter may be in the form of arbitrary or world time signals. All accelerographs have built-in calibration systems.

a. Analog, surface

These are self-contained three-component systems that record continuous data traces on a strip chart or photographic film. There is no electronic signal conditioning (amplification or filtering) of input seismic motion. The instrument normally triggers on an early phase of P-wave arrival.

Frequency range 0.1 to 30 Hz
No pre-event memory
Time code or radio time
Self-triggering
Triaxial accelerometers $3,000
Many years of field experience

b. Analog, down-hole

Transducers may be located at some distance from the recorder. Signals are transmitted by wire to a central recording unit where as many as 13 channels of data are amplified and recorded photographically. The triggering system is the same as described for the analog surface accelerograph.

Frequency range 0.1 to 30 Hz
No pre-event memory
Time code or radio time
Self-triggering

3 channel	(no cable cost included)	$ 8,000
6 channel	"	$11,000
9 channel	"	$14,000
12 channel	"	$17,000

Two years field experience

c. Digital, surface

This surface accelerograph is a self-contained three-component system that records digital acceleration data on magnetic tape cassettes. A pre-event memory allows recording of the entire earthquake.

Frequency range 0.1 to 30 Hz
Dynamic range, full scale/resolution
is 66 db (1/2048 resolution, 12 bit ADC)
2.5 sec pre-event memory
100-200 sps data rate/channel
Time code or radio time
Self-triggering
Triaxial accelerometers $5,000
Two years field experience

b. Digital, down-hole

This unit is the same as the digital surface system except the transducer capsules may be installed at locations some distance from the recorder.

Same specs as above

3 channel	(no cable cost included)	$ 9,000
6 channel	"	$15,000
9 channel	"	$21,000
12 channel	"	$27,000

No field experience

2. Velocity systems

   The velocity instrumentation available is capable of recording three channels of single, dual or treble gain data on an FM magnetic tape recorder.

   Frequency range 0.025 to 20 Hz
   Max velocity 100 cm/sec
   Sensitivity 5 or 0.5 or 0.05 v/cm/sec
   (3 simultaneous outputs per channel available)
   FM analog recorder
   Size (3-axis) 40 x 30 x 15 cm
   Weight (sensors only) 15 kg

3-axis, 1 sensitivity	$10,000
3-axis, 2 sensitivity	$16,000
3-axis, 3 sensitivity	$22,000
One year field experience	

Systems Requiring Development

1. Extended dynamic range digital accelerograph

   This category of instrumentation is capable of recording a wide range of acceleration levels using a system of amplifier switching regulated by the magnitude of input signals. Prototype systems have been developed. Further development and field testing is required.

   Specification based upon prototype seismographs presently available using microprocessor control,
   Frequency range 0.1 to 30 Hz
   Dynamic range (12 bit ADC plus 256X gain-ranging amplifier) 120 db
   Pre-event memory
   Short term/long term averaging logic for triggering
   100 sps data rate/channel
   20 min recording time
   Time code or radio code
   Triaxial accelerometers $9,000
   No field experience

2. Pore-pressure measurements

   Electrical output pore-pressure sensors are available and have been used in embankments. Generally they are not as reliable as static piezometric systems. Dynamic recording using analog or digital systems compatible with the accelerograph can be done with some interface design.

3 pressure sensors recorded on a digital cassette recorder (no cable costs included) $5,000
No field experience

Systems Requiring Design

1. Relative displacement measurements

This instrumentation would be designed to record relative displacement using a comparative system providing electronic conditioning of data from a dual set of accelerometers. The following design requirements apply to this type of instrumentation.

a. $\Delta\ddot{x}(t)$ must be recorded directly through an amplifier so as to use the dynamic range of the recorder.

b. Random noise must be characterized and then minimized. For example, a signal-to-noise ratio of 100:1 represents a displacement uncertainty of 3.5 cm at 0.1 Hz using a 0.1g relative acceleration system.

c. Long term relative drift must be characterized and compensated.

d. One to two years development and field tests required before deployment.

2. Point angular measurements

This measurement system is intended to record in an acceleration or velocity mode the rotational motion at a point.

a. Possible sensors

Angular Velocity (Japan)
Frequence range 1.0 to 30 Hz
Angular displacement limit $\pm 10^{\circ}$
Millivolt level output

Angular Accelerometer (USA, USSR)
Frequency range 0.1 to 20 Hz
Full Scale Angular acceleration 0.25 rad/sec
Volt level output

b. Further study required
Cross-talk terms should be examined
Coupling of instrument to soil

5.3 BASIC ARRAY COSTS

All cost estimates for arrays are based on instrumentation consisting of digital accelerographs which record 12 acceleration bits and time code information on magnetic tape. This accelerograph operates in a self-triggering mode and will be equipped with a pre-event memory for 2.5 sec of data before the trigger signal. It will operate in the range 0.001g to 2.0g. The estimated costs are $5,000 per accelerograph, $2,000 for site preparation and installation for each instrument and $10,000 for site investigation at each array. Additional investigations will be required in some locations which have been insufficiently mapped.

Table 5.1 lists the basic California costs for establishing the four types of arrays designed for source mechanism and wave propagation studies. The $120,000 shown for laboratory facilities supplies and test and repair equipment is equivalent for each array since identical items are required regardless of the number of instruments in a particular array. Note that this would be a single joint cost if the local effects array was combined with one of the source mechanism-wave propagation arrays. The operation cost is rated at $800 per instrument.

Strike-Slip Source and Wave Propagation Arrays

It is assumed that the basic array to investigate mechanisms of strike-slip sources is composed of 105 instruments arranged in a comb-like pattern with teeth perpendicular to the strike of the fault (Fig. 3.1). The comb will parallel 500 km of fault using 50 instruments for its spine, and another 35 comprising 5 teeth of 7 instruments each, and an extended tooth of 20 instruments. Capital costs of instruments for such an array will be $525,000. An additional $105,000 will be required for site preparation, and $105,000 for installation in a typical California type location.

Subduction-Thrust Source and Wave Propagation Arrays

It is assumed that the basic array for investigation of subduction thrust sources will be a three-row linear array of 25 instruments per row at 20 km intervals, along 500 km of fault (Fig. 3.2). Capital costs of instruments will be $375,000, costs of site preparation $75,000, and installation $75,000.

Dip-Slip Source and Wave Propagation Arrays

It is assumed that the basic array for investigation of dip-slip sources will be a square grid of instruments at 5 km intervals in an area roughly 50 km x 50 km (Fig. 3.3). There will be 100 instruments costing $500,000. Site preparation will cost $100,000 and installation an additional $100,000 in a typical location.

Mobile Arrays

Opportunities will arise to carry out source mechanism studies on aftershock sequences ($M = 6.0$ to 6.5) of large earthquakes. In addition

TABLE 5.1

BASIC DEVELOPMENT COSTS FOR SOURCE MECHANISM AND WAVE PROPAGATION ARRAYS
(DOLLARS X 1000)

Array Type	Length (km)	Instruments (Number	Instruments ($)	Site Preparation and Installation ($)	Site ($) Investigation	Other* ($)	Total Development ($)	Annual Operation ($)
S	500	105	525	210	10	120	865	84
T	500	75	375	150	10	120	655	60
D	50	100	500	200	10	120	830	80
M	-	50	250	100	5	120**	475	40

*Cost includes laboratory facility and special test and repair equipment; to be a single cost when more than one array type is developed at at single location

**Less the cost of permanent laboratory housing

Legend of Array Types

S - Strike-Slip
T - Subduction Thrust
D - Dip-Slip
M - Mobile

the capability to quickly install an array in response to credible predictions will be required. An array which could be rapidly moved either to function on its own or to augment an existing source or local effects array could consist of 50 instruments, costing $250,000. Cost of portable housing to protect the instruments in field would be $500 per unit. Combined costs for instruments and housing would be $275,000.

A mobile array could be stored in conjunction with a fixed array, and would be maintained by the same staff. Mobilization cost in a country where the earthquake occurred, would be $10,000. During a series of aftershocks, redeployment may be made. The cost would be $5,000 for each redeployment. Therefore, for aftershock measurements a one-time cost of $30,000 is estimated. This estimate excludes cost of transportation of personnel and instruments between the laboratory where the instruments are stored and the country where the large earthquake has taken place. This transportation cost varies widely depending on where the aftershock measurements are conducted. In addition, site investigations may be necessary; however, this cost is estimated at half the $10,000 anticipated for the fixed arrays.

Local Laboratory Arrays

The Local Laboratory Array has been envisioned as a system capable of recording 90 channels of acceleration data on and below the ground surface over an areal extent of approximately 500 m square (Fig. 4.1). The instrumentation consists of 30 triaxial transducers, 15 located on the ground and 15 down hole, with the data transmitted by cable to a central location where it is recorded in a digital format on magnetic tape. Since the recorder house would be located within the array, cable runs would not exceed 350 m. The down-hole transducer packages are assumed to be emplaced to depths of approximately 100 m at eight different locations. All units are to be interconnected for simultaneous starting and timing signals.

The central recording system has been chosen to simplify the preparation of facilities, maintenance of the established system, and security of the data collection process.

The housing for the recorders would be the laboratory headquarters and would be equipped with equipment and supplies necessary for testing, routine maintenance and repair of all elements of the array.

Table 5.2 presents a breakdown of the $519,000 required to establish this typical array. Item 1, the site investigation, is a geotechnical evaluation of the array location and includes a geological reconnaissance, shallow refraction studies and logging of a sample drill hole (soil/rock type, densities, P and S-wave velocities, etc.) to be used later as an emplacement site for the 100 m depth transducer package. Item 2 lists the instrumentation and accessory hardware items necessary for installation and maintenance over the first year. Item 3 shows the costs of site preparations and installation for the surface and downhole transducers and for the data cable runs that go to the central

TABLE 5.2

LOCAL LABORATORY ARRAY DEVELOPMENT COSTS
(DOLLARS X 1000)

1. Site Investigations	10
2. Instrumentation	
7 Surface triaxial accelerometer units with recorders (21 channels x $1800)	37.8
1 Down-hole installation; 7 triaxial accelerometer units and recorders (21 channels x $2500)	52.5
2 Down-hole installations; each with 3 triaxial accelerometer units & recorders (18 channels x $2500)	45
5 Down-hole installations; each with 2 triaxial accelerometer units & recorders (30 channels x $2500)	75
Data cable	14
Conduit, Junction boxes, etc.	10
Spare parts and supplies	42
3. Installation	
Site preparations	
Downhole	88
Surface	7
Data cable emplacement	18
4. Laboratory Headquarters	
Building construction	50
Interior preparations	20
Testing and maintenance equipment	50
Total Development Costs	519.3
5. Maintenance (annual)	24

recording facility. Item 4 covers the construction of a permanent laboratory headquarters for all array operations and includes interior preparations such as terminal box installations, recorder racks, etc. and the acquisition of testing and maintenance equipment. Item 5 is an estimate of annual maintenance costs.

Simple Extended, Elemental and Special Arrays

Due to the special nature of Simple Extended, Elemental and Special Arrays and the great variation in design details which may exist, no specific system costs for these types of arrays are presented here. However, it is felt that the cost figures provided for instrumentation, installation and maintenance of other types of arrays could readily be used to estimate the cost of any specific array configuration of this type.

Maintenance Facilities

Permanent housing would be required at fixed array sites including both the laboratory facility and residence quarters for maintenance personnel. These structures and testing and maintenance equipment are specified separately although the laboratory arrays would be combined, as appropriate, with larger arrays of instruments. The cost is estimated at $120,000 for each array. This cost essentially remains constant because the same housing and equipment is required for 50 instruments as is required for 105 instruments.

Summary of Costs for a Dense Array

Table 5.3 presents the California based development and operating costs for an array using analog accelerographs, 100 self-contained surface units in combination with three down-hole systems. Note that these estimates include personnel salaries during planning, installation and maintenance phases. Amortizing the equipment purchase over the first two years gives array development costs of $265,000 and $371,000 respectively for years one and two, and $65,000 for maintenance during each succeeding year.

5.4 ADJUSTMENTS FOR SUGGESTED LOCATIONS

Table 5.4 gives a "Site Factor" for each of the locations selected as promising for the deployment of strong-motion arrays. The Site Factor is a multiplier for the cost figures given in Table 5.2. Also indicated is the anticipated type and size of array which might be deployed at the site. For instance the Tohoku array would cost 1.25 times the cost in California. Of course this would be reduced by a smaller array dimension and the consequent lesser number of instruments.

TABLE 5.3

SUMMARY OF COSTS FOR A DENSE ARRAY

Instrumentation	
Surface: 100 @ $3,000 = (SMA-1 with time code generator)*	$300,000
Downhole: 3 @ $10,000 = (CRA-1 + Triggers + time code generator + cable)**	$ 30,000
	$330,000
Instrument Shelters	
103 @ $1,000 = (Fiberglass shelter + conc. pad)	$103,000
Down-hole Installations	
Drill Rig: 3 @ $6,600 = ($600/day on-site + $300/day in transit 10 days each site + 2 days in transit)	$ 20,000
Hole log & Properties: 3 @ $3,300 = (log, blow count, P&S wave)	$ 10,000
Misc. supplies and material	$ 3,000
	$ 33,000
Instrument Shop On-Site	
Armco building (steel prefabricated)	$ 20,000
Site preparation	$ 5,000
Finishing + darkroom	$ 5,000
Equipment	$ 20,000
	$ 50,000
On-Site Housing in Remote Area	
Prefab house	$ 30,000
Site preparation	$ 10,000
	$ 40,000
Special Equipment	
Printers and Duplicators	$ 20,000

TABLE 5.3 (CONCLUDED)

Schedule and Personnel Costs

First Year: Planning

Detailed planning	$ 20,000
Full-time technician (Salary and overhead)	$ 25,000
Training (Travel & Per Diem)	$ 5,000
	$ 50,000

Second Year: Installation

2 Technicians $ $25,000	$ 50,000
2 Assistants @ $15,000	$ 30,000
Travel and Per Diem	$ 20,000
Misc. Supplies and Expense	$ 10,000
	$110,000

Succeeding Years: Maintenance

1/2 time supervisor (Salary & overhead)	$ 25,000
Technician (Salary and overhead)	$ 25,000
Travel & Vehicle	$ 6,000
Supplies & Expense	$ 6,000
Misc. Equipment & Parts	$ 3,000
	$ 65,000

Summary Budget

First Year Total (1/2 equipment cost & facilities + planning)	$265,000
Second Year Total (1/2 equipment cost + installation)	$371,000
Succeeding Years total (Maintenance)	$ 65,000

*The SMA-1 is a three-channel self-contained photographic recording accelerograph

**The CRA-1 is a multi-channel (up to 13 data traces) photographic recording accelerograph, with the transducers located remote from the recorder

TABLE 5.4

SITE FACTORS AND TENTATIVE DIMENSIONS FOR SELECTED ARRAY LOCATIONS

Location	Site* Factor	Type of Array	Size (km)
Adapazari	1	S	200
Antigua	2.5	T	300
Arica	2	T	300
Calabria	1.25	D	50
Chia-i	1	S	400
E. Tohoku	1.25	T	200
Garm	1	S	400
Gonabad	1.5	S	300
Granada	1	D	50
Ica	2	T	300
Kamchatka	2	T	500
Oaxaca	2	T	400
Palmdale	1	S	500
Patras	1.5	S	30
Quezon	2	S	300
Salt Lake	1	D	500
San Juan	1.5	D	200
Shantung	1	S	500
Shillong	1.5	T/S	300
Struma	1.25	D	100
Suruga-Izu	1	T/S	100
Teheran	1	T/S	200
Vancouver Is.	1	S	500
Varto	1.5	S	400
Wellington	1.25	S	100
W. Chubu	1	S	200
W. Java	2.5	T/S	500
Yakutat	3	S	20

*Indicates multiplier for array costs compared to California base in Table 5.2.

5.5 PERSONNEL, OPERATIONS, AND DATA MANAGEMENT

The availability of personnel capable of operating a network at a 90% probability of obtaining good records during an earthquake will vary widely from country to country. Relevant factors are national population, degree of technical sophistication of the society and a factor that encompasses such intangibles as responsibility and devotion to duty. For people of given technical qualification, a 90% level of instrument reliability will not necessarily follow. Sometimes it may be more cost effective to transport and house suitable personnel than to use local workers, even though the latter are adequately qualified on paper.

As arrays become established, the optimum training scheme will be an in-service one, so that any new array will have a content of experienced operators, and the operation of an old array will provide new operators with experience. Travel budgets for this purpose should be continuously provided.

Operations

During the first year of array development, most of the effort would be directed toward acquiring equipment and training personnel. During the second year, the effort would be directed toward installation of instrumentation and "debugging" of individual and interconnected systems. During the third year, operations should settle into a routine procedure consisting of maintenance and calibration of individual accelerographs at three month intervals and central recording systems at one month intervals. These schedules would be flexible and would be adjusted as the array(s) reliability is established. In event of significant earthquakes, data would be collected at individual sites as quickly as appropriate.

Data Management

Provision for the playback of recorded data in analog form, and for the duplication of raw data, must be made in each country maintaining an array. This is the only way to ensure that original data is not lost or misidentified.

Reduction of data to standard form should be performed in three regional data centers: North America, Asia, and Europe or the Middle East. The data should conform as closely as possible to the standard format established by Caltech or should be capable of being read by computer programs which will read Caltech format. These centers should store the earthquake parameters including origin time, epicenter coordinates, depth and magnitude and station information including instrument coordinates, orientation, calibration constants and acceleration data. This information should be to the same specification at all data centers.

Every three months, the three regional clearing houses described above should circulate bulletins to all involved institutions describing records obtained. In addition a catalog of records should be prepared on a computer data base which may be accessed by a telephone terminal. By pursuing such a policy of free and convenient interchange of data, and by allowing frequent visits of personnel between sites, narrow attitudes regarding data ownership should be overcome.

Present methods of exchanging earthquake data rely on punched cards for individual records and magnetic tape for groups of records. Both of these are inconvenient on an international basis because cards are bulky and magnetic tapes are inappropriate for the rapid circulation of individual earthquake records. A move to readily exchangeable cassette tapes or floppy discs could help in this regard.

5.6 SUMMARY

Instrumentation available for the development of large regional or comprehensive local arrays is divided into three categories:

1. Instruments that are currently in use. These include analog and digital accelerographs and analog velocity recording systems.

2. Instruments requiring development. Although subcomponents are available they have not been integrated into a single operating unit; these include extended dynamic range digital accelerographs and pore-pressure recording systems.

3. Instruments requiring design. Potentially useful measurement systems in this category would record relative displacement and angular acceleration or velocity.

Five types of arrays have been considered; three designed for source mechanism-wave propagation studies, one as a mobile array for recording aftershocks or for location at high probability prediction sites, and one planned as a laboratory to study local effects. The standard instrument considered for these arrays is a three-component digital accelerograph with an estimated export price of $5000 per unit. The costs in California for construction of "typical arrays" are as follows:

Strike-slip fault	105 instruments	$865,000
Subduction thrust fault	75 "	$655,000
Dip-slip fault	100 "	$830,000
Mobile Array	50 "	$475,000
Local Laboratory Array	30 "	$519,000

The mobile and local laboratory array could be combined with a source mechanism-wave propagation array providing a consolidation of some expenses and use of personnel.

The twenty eight sites selected as promising for the deployment of strong-motion arrays have been evaluated for probable array dimensions and for site factors that relate development costs to that in

California. By comparing the array dimensions with a "typical array" and by considering the site factor, simple calculations provide estimated costs of different sized arrays at different locations.

Each array (or combined arrays) would have its own operating headquarters staffed by personnel from that country and if necessary supplemented by trained personnel from other areas. Earthquake data collected by the operating group would be duplicated and transmitted to regional data centers, tentatively identified for location in North America, Asia, and Europe or the Middle East. The data centers would store earthquake and station information in a telephone-accessed computer and would periodically disseminate bulletins and digital strong-motion data to interested institutions on an international basis.

Chapter 6

Implementation

6.1 INTRODUCTION

The procedures outlined here for the implementation of an international strong-motion instrument array program are flexible and not completely defined. There are strong reasons why this should be the character of the recommendations. The intention is to develop a program that is controlled by the participating scientists, and this constraint excludes an organization that is tied to existing international inter-governmental organizations. The governments of few countries have placed strong-motion earthquake studies high on their list of national priorities and, even when a commitment to such a program has been made, procedures for transfer of funds or resources from national treasuries into a cooperative research structure, as herein conceived, are not clear for any country. Under the stimulus of an international program, as outlined in this volume, such placement of priorities and specification of procedures may ultimately occur. However, for the time being it is felt appropriate to design an implementation structure that will accommodate present realities. It is hoped that, subsequent to initiation of cooperative programs under this structure, the desirability and need of a stronger structure will become apparent to the countries concerned and ways of fashioning such a structure will be developed.

It is felt to be important to tie the implementation structure directly to the International Association for Earthquake Engineering (IAEE), as this is an existing organization. Members from all countries represented at the Workshop belong and it is an organization dedicated to the goals of this program. As will be seen, some supervisory and advisory functions are attached to a Council organized under the auspices of IAEE, with appropriate representation from the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and other relevant organizations. At present, though membership on this Council will be recommended by IAEE, actual participation will depend on the decision of each country to support its member, or members, on the Council.

A truly international program, as herein conceived, will require the dedication of some level of national resources. It is undoubtedly true that some countries will assume larger commitments of resources than other countries, but commitment by all, at some level, is an aspect of the implementation structure herein recommended.

The proposed structure recognizes that governments, at present, are unlikely to commit a segment of national resources into a general fund to be disbursed under the recommendations of an international panel of scientists. Thus, the concept of the proposed Council is that of a group formulating specific plans out of the generalized recommendations of this Workshop report. The Council and its committees will recommend standards for data acquisition and disbursal, etc. All actual cooperative projects will be organized on bilateral, or multilateral bases; and the selection of projects to be undertaken will, hopefully, conform to the recommendations of the Council or of one of its committees. This implementation structure allows freedom for each country to have clear knowledge of how its resources are being used and to make individual commitments for each project it wishes to join.

6.2 IMPLEMENTATION STRUCTURE

The proposed implementation structure is shown Figures 6.1 and 6.2. The International Strong Motion Array Council (ISMAC) has for its parent organization the International Association for Earthquake Engineering. ISMAC will appoint committees C_0, C_1, C_2, C_3 and C_4 that have specified responsibilities. In the chart, SC_{11}, SC_{12}, etc., represent Steering Committees for specific instrument arrays and P_1, P_2, etc. represent specific projects involving different types of instrument arrays. UL and ML indicate specific unilateral or multilateral array projects that will be initiated in the future, or that may be underway at the time ISMAC is organized.

International Strong Motion Array Council (ISMAC)

1. Constitution

   a. The International Association for Earthquake Engineering should take immediate steps to establish and organize ISMAC.

   b. Membership in ISMAC should be determined by IAEE (including representation from other organizations such as IASPEI).

   c. ISMAC should draft and adopt bylaws in consultation with IAEE.

   d. IAEE should seek financial support for ISMAC until such a time as ISMAC can obtain funds to support its Council office and normal operations. Until funds are obtained, the IAEE Central Office should be expanded to handle Council work. (The IAEE Central Office is now located in Tokyo and operates under the auspices of the Japan Society for the Promotion of Earthquake Engineering. This organization has indicated willingness to arrange for the expansion necessary to handle Council work.) After ISMAC becomes a financially viable organization, it could

FIGURE 6.1

Implementation Structure

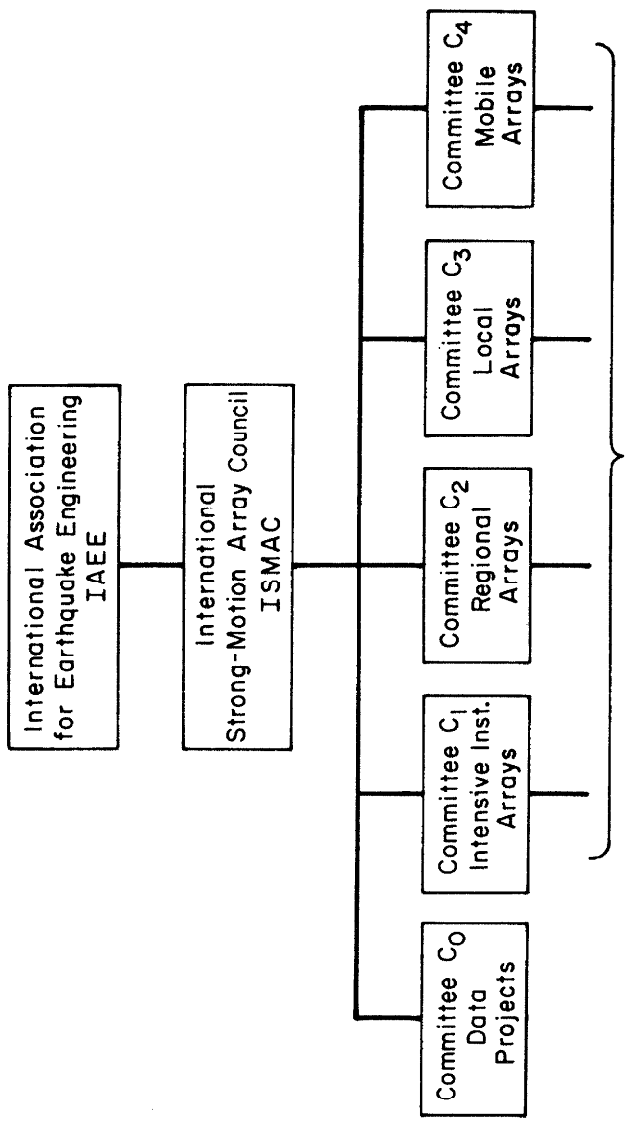
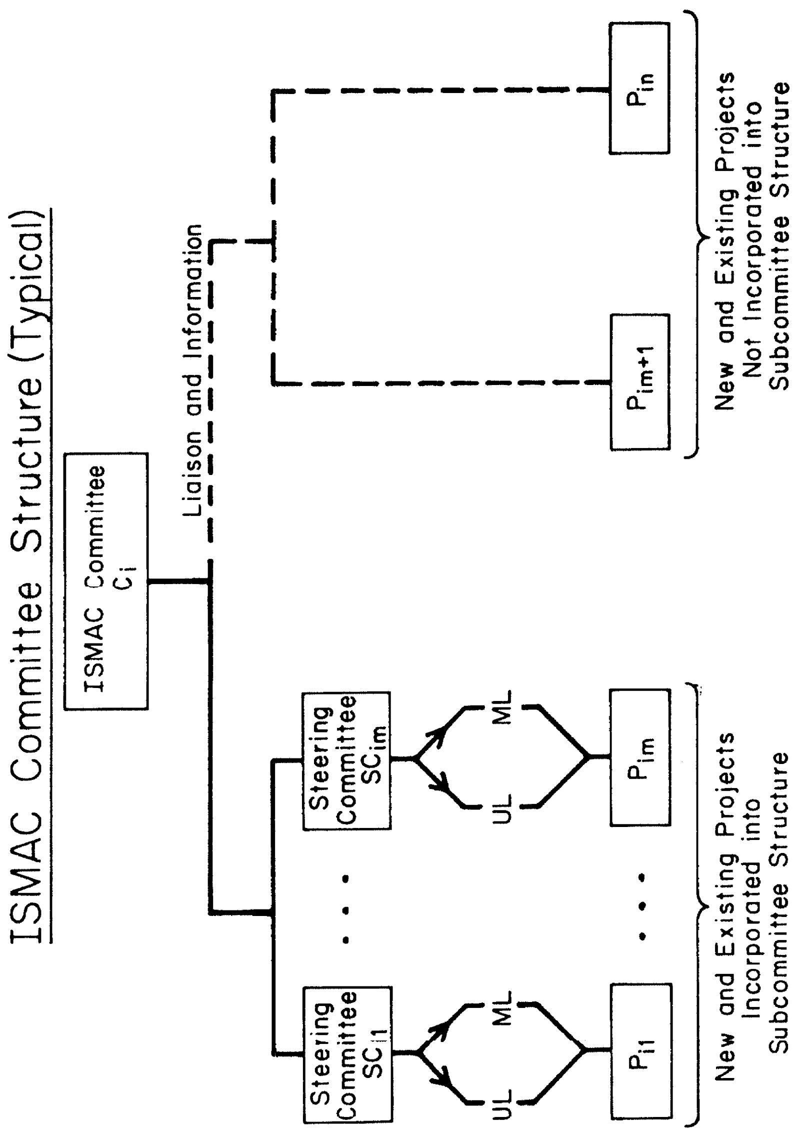


FIGURE 6.2


ISMAC Committee Structure (Typical)
ISMAC Committee C_i
Liaison and Information
Steering Committee SC_{i1}
Steering Committee SC_{im}
UL
ML
UL
ML
P_{i1}
P_{im}
P_{im+1}
P_{in}
New and Existing Projects Incorporated into Subcommittee Structure
New and Existing Projects Not Incorporated into Subcommittee Structure

decide to move its headquarters from time to time in the interest of better carrying out its responsibilities.

e. Until ISMAC funding is established, the expenses of members should be met by their respective countries. Until such support is established, members should pay their own expenses.

f. IAEE, through member National Societies, should inform the National Governments of the need for developing methods for supporting cooperative international scientific earthquake hazard mitigation research and studies.

2. Functions

a. Hold at least one meeting each year and transact other business by correspondence. The agenda and minutes of all meetings should be transmitted to IAEE which may choose to dispatch observers to any particular meeting as it deems appropriate.

b. Disseminate information about ISMAC activities, strong-motion array projects, and publications.

c. Recommend the initiation of needed projects by appropriate agencies.

d. Prepare general guidelines for arrays.

e. Recommend priorities for array locations.

f. Appoint and coordinate committees C_0, C_1, C_2, C_3 and C_4.

g. Coordinate the assembly and exchange of data.

h. Seek funding for ISMAC operating expenses and for special projects.

ISMAC Committees

1. Committee C_0 - Data Projects

The function of this committee is to arrange the dissemination of strong-motion earthquake data in a form helpful to those who can make use of it. This includes not only data generated by the proposed Strong-Motion Arrays, but also existing strong-motion data, in various countries, that is not readily available at present. This may require processing of the data and preparation of reports. Because strong earthquakes occur in many different countries, and even in any one country several different organizations may be responsible for national earthquake data, it is difficult for individual research workers to know what data exist and how to get access to them. Because of this, Committee C_0

should carry out the following projects, or should arrange for them to be done by appropriate agencies:

a. Preparation of a catalog of existing, significant, strong-motion earthquake data, which gives a brief description of the data and the agency in whose possession they are.

b. Preparation of a catalog of strong-motion accelerograph locations (world-wide). This catalog should identify the location of each strong-motion accelerograph in every country, identifying the instrument and the agency in charge of it.

c. Preparation of a catalog of existing special strong-motion arrays. At present there are only a few, small, strong-motion instrument arrays in the world, but these should be identified and, as new and more elaborate arrays are installed they should also be described in the revised catalog.

d. Preparation of a catalog of existing down-hole instruments and arrays; both strong-motion and conventional seismological instruments. A number of these installations exist in some countries but there is, at present, no compilation giving a description of the array, its location, the type of instruments deployed, and the local geology.

e. Publication and dissemination of significant strong-motion data. Strong-motion records are being obtained in a number of different countries and are in the possession of a variety of different agencies. It is important that all significant records be published so as to be available for study by all concerned.

f. Preparation of a catalog of available bore-holes that could be instrumented. In some countries, there are existing bore-holes which have been drilled for other purposes but which might be available for the installation of strong-motion instruments.

h. Preparation of a catalog of existing strong-motion instruments and other equipment that are available for rapid deployment to record aftershock data either within the country of ownership or within some other country.

i. Development of standard strong-motion data reporting procedures.

2. <u>Committee C_1 - Intensive Instrumentation Arrays</u>

This committee should be prepared to advise and to guide large projects such as those recommended for source mechanism and wave propagation studies with the possible overlapping of Local Laboratory Arrays. Specific tasks that the committee should undertake are:

a. Recommend model research array plans.

b. Recommend desirable instrument specifications.

c. Recommend maintenance schedules.

d. Recommend standard data recovery procedures.

3. Committee C_2 - Regional Arrays

This committee should be prepared to advise and to guide projects such as stand alone Local Laboratory and Simple Extended Arrays. Specific items that the committee should undertake are:

a. Recommend model research array plans.

b. Recommend desirable instrument specifications.

c. Recommend maintenance schedules.

d. Recommend standard data recovery procedures.

4. Committee C_3 - Local Arrays

This committee should be prepared to advise and to guide projects such as Elemental Arrays and Special Arrays. Some specific tasks that should be undertaken by the committee are:

a. Recommend model research array plans.

b. Recommend desirable instrument specifications.

c. Recommend maintenance schedules.

d. Recommend standard data recovery procedures.

5. Committee C_4 - Mobile Arrays

This committee should be prepared to advise and to guide projects relating to mobile arrays. Some specific tasks that should be undertaken by the committee are:

a. Recommend desirable instrument and equipment specifications.

b. Recommend maintenance schedules.

c. Recommend standard data recovery procedures.

d. Ascertain potential for in-country availability of instruments and equipment for rapid deployment in selected highly seismic regions; both in-country and out-of-country.

e. Ascertain potential for rapid out-of-country deployment of strong-motion instruments and equipment into countries likely to experience large magnitude earthquakes. Ascertain necessary arrangements in each country and, insofar as possible, complete all preliminary arrangements that would facilitate rapid deployment.

6.3 PLANNING AND EXECUTION

The planning and execution of individual array projects should proceed as indicated in Fig. 6.2. The establishing of a Steering Commitee for each array has many positive features. Yet, it is recognized that this structure may not be appropriate for every array project. Where no Steering Committee exists, it is strongly recommended that some other mechanism for liaison and information transfer between the project and the relevant ISMAC Committee be established.

Intensive Instrumentation Array Projects

The following guidelines are recommended for the planning and execution of intensive instrumentation array projects such as those required for comprehensive source mechanism and wave propagation studies combined with Local Laboratory Arrays.

1. Steering Committees; $SC_{11},\ldots,SC_{1n}$

A Steering Committee for each array should be formed jointly by the Funding Countries and the Site Country in consultation with ISMAC Committee C_1. The Steering Committee should have the following functions:

a. Formulate overall design/specifications for the array and its instruments, consulting with Committee C_1.

b. Partition array design and construction into logical portions that can be efficiently accomplished.

c. Recommend responsibility of individual participating countries for specific portions (see 2 below).

d. Replan array as required by available funding.

e. Select the implementing institution, or institutions, that will carry out the actual work.

f. Oversee the implementation of the program.

2. Participating Countries

The responsibilities of each participating country will be as follows:

a. Nominate representative members of the Steering Committee.

b. Review the design of the array as recommended by the Steering Committee under Item 1.a.

c. Determine the level and nature of participation.

d. Arrange funding (through own resources, or seek financial aid).

3. Site Country, or Countries

The responsibility of a Site Country will be to:

a. Nominate representative members of the Steering Committee.

b. Review the design of the array as recommended by the Steering Committee, under Item 1.a.

c. Determine the level and nature of participation.

d. Arrange funding (through own resources, or seek financial aid).

e. Arrange for long-term operation and maintenance through direct funding, or other sources.

f. Report all resulting strong-motion data to ISMAC on a timely basis.

4. Implementing Institution, or Institutions

The responsibilities and duties of an Implementing Institution (research laboratory, university, etc.) will include the following:

a. Receive funds, equipment, etc., from participating countries.

b. Receive management instructions from the Steering Committee.

c. Make progress reports to the Steering Committee.

d. Implement the program.

e. Award contracts as required.

Regional Array and Local Array Projects

The following guidelines are recommended for the planning and execution of the array projects such as stand alone Local Laboratory Arrays, Simple Extended Arrays, Elemental Arrays and Special Arrays.

1. Steering Committees; $SC_{21},\ldots,SC_{2n}, SC_{31},\ldots,SC_{3n}$

A Steering Committee should be formed by individual countries unilaterally or by participating countries multilaterally in consultation with the appropriate ISMAC Committee. A Steering Committee will perform the following functions.

a. Design the array plan and the instrument specifications, consulting with Committees C_2 or C_3.

b. Redesign the array, if necessary, after review by the countries involved.

c. Select implementing institution, or institutions.

d. Oversee the implementation of the program.

2. Participating Countries

Participating countries will have the following responsibilities:

a. Form a Steering Committee individually, or multilaterally.

b. Review the design of the array.

c. Finance specific sites, installation, and long-term operation and maintenance.

d. Report all resulting data to ISMAC, on a timely basis.

3. Implementing Institution, or Institutions

An Implementing Institution will have the following responsibilities and duties:

a. Receive funds, equipment, etc.

b. Receive management instructions from Steering Committee.

c. Implement the program.

d. Award contracts as required.

e. Make progress reports to the Steering Committee.

Mobile Array Deployment

The following guidelines are recommended for the planning and execution of Mobile Array projects.

1. Steering Committees; $SC_{41}, \ldots, SC_{4n}$

An *ad hoc* Steering Committee should be formed for each earthquake monitored. The functions of this Steering Committee are:

a. To be organized on the site by the representatives of the countries participating in the monitoring of aftershocks of a large earthquake.

b. Plan procedures for deployment, based on specifications and time of availability of equipment from each country.

c. With participation of the Host Country, the Steering Committee will arrange for the central assembly of data and transmission in approved format to ISMAC on a timely basis.

2. Participating Countries

A country that participates in a mobile array should have the following responsibilities and duties.

a. Participate in the Steering Committee.

b. Arrange for maintenance and operation of its own equipment.

c. Transmit all data to the central facility on a timely basis.

3. Host Country

The responsibilities and duties of the Host Country should include:

a. Arrange for central communications, workshops, and housing.

b. Arrange for access to epicentral area by field crews from participating countries.

c. Arrange for data reproduction facilities and transmit total data set to ISMAC on a timely basis.

Unilateral and Multilateral Projects

Individual countries can now proceed with unilateral projects within their boundaries, and existing agreements between some pairs of countries make it possible for bilateral projects to be undertaken. There appear to be, at present, no existing agreements or procedures that make it possible to undertake multilateral projects that involve three or more countries. However, there is no reason why appropriate arrangements cannot be developed in the future. As the governments of concerned countries become aware of the benefits that can be derived from the installation of the arrays described in this report, cooperative ventures will hopefully be undertaken.